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MODELLING OF PARTICULATE MATTER AND AMMONIA EMISSIONS FROM GERMAN AGRICULTURE

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Dedicated to the dearest and beloved friend Juan Guillermo Cobo

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a	annum
AA	Amino acids
ae	aerodynamic diameter
ap	animal place
BAT	Best Available Techniques
BAU	Business-as-usual
BB	Brandenburg
BS	Braunschweig
BW	Baden-Württemberg
C/N ratio	Carbon-nitrogen ratio
CAP	Common Agricultural Policy
CC	Cross Compliance
CEC	Cation Exchange Capacity
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CLRTAP	Convention on Long-range Transboundary Air Pollution
CP	Crude protein
Cu	Copper
DFG	Deutsche Forschungsgemeinschaft
EA	Exhaust Air
EATS	Exhaust Air Treatment System
EC	European Community
EFEM	Economic Farm Emission Model
EU	European Union
FKW	Perfluorinated organic compounds
FR	Freiburg
H-FKW	Halogenated fluorocarbon
H_2S	Hydrogen sulphide
HA	Hannover
HC	Health Check
IIASA	International Institute for Applied Systems Analysis
IPPC	Integrated Pollution Prevention and Control

KR	Karlsruhe
kt	kilotons = 10^3 tons
GAS-EM	name of model used for calculation of National Imission Inventory Report (NIR) outputs
GHG	Greenhouse gases
GWP100	Global Warming Potential for the time horizon of 100 years
LS	Lower Saxony
LU	livestock unit
LÜ	Lüneburg
LRTAP	Geneva Convention on Long-range Transboundary Air Pollution
MAC	Maximum acceptable concentrations
ME	Metabolized Energy
Mg	Magnesium
Mn	Manganese
N	Nitrogen
NAU	Niedersächsische Agrar- Umweltprogramme
NEC	National Emission Ceilings
NIR	National Imission Inventory Report
NMVOC	Non-methane volatile organic components
NO, N_2O	Nitrous oxides
NO_3	Nitrate
NO_x	Nitrogen oxides
NH_3	Ammonia
KULAP	Kulturlandschaftsprogramm
MEKA	Marktentlastungs- und Kulturlandschaftsausgleich
pH	measure of the acidity
PM_{10}	Fine particles with an aerodynamic diameter of less than 10 µm
$PM_{2.5}$	Fine particles with an aerodynamic diameter of less than 2.5 µm
POP	persistent organic pollutants
SF_6	Sulphur hexafluoride
SO_2	Sulphur dioxide
SO_4	Sulphate
TAN	Total ammoniacal nitrogen
TiO_2	Titanium dioxide/ titania
TSP	Total suspended particulate matter
TÜ	Tübingen

UBA	Umweltbundesamt
UNEP	United Nations Environment Program
VOC	Volatile organic compounds
WE	Weser-Ems
WHO	World Health Organization
Zn	zinc/ spelter
ZnO	Zinc oxide

1 GENERAL INTRODUCTION

1.1 Background

Agriculture was, is, and will be an essential source of food for the whole humanity. Furthermore, it is an important basis of livelihood for more than 50% of the planet population (FAO, 2000). Nowadays, agricultural activities are expanded far beyond food sector, primarily in the direction of the high profit oriented non-food products such as bio-fuel and biogas.

Beyond this, agriculture is regarded as the production sector causing environmental degradation and carrying the burden of its consequences. For example, improper land management causes soil erosion, which, in turn, leads to yield reduction and air and water pollution. The solutions for environmental problems have to be searched for in all areas, where particular pollution arises, firstly, because of specific characters of pollution stemming from various economy sectors, and secondly, as it is easier to combat pollution before it spreads far away from its emission source.

Several studies have been conducted to understand the characters of environmental problems caused by the agricultural sector and to find out better mitigation options. Thank to extensive research, the contribution of the agricultural sector to negative environmental changes through emissions of ammonia (NH_3) and green house gases (GHG) is now evident. Moreover, it has been revealed that the major pollutants (i.e., gas and dust) in agriculture result from natural processes (UBA, 2005), although anthropogenic activities performed in the agricultural sector are boosting the intensity of naturally occurred emissions.

If natural processes are hardly controllable, negative impacts of anthropogenic factors can be minimized, e.g., through the introduction of the best farming practises and measures preventing erosion (UBA, 2005). Plenty of ideas, on how to abate emissions from agriculture, have been generated, and even several of them have already been proven as efficient and taken into everyday practise. Nevertheless, the current knowledge on the specific role of the agricultural sector in environmental changes is not sufficient on the background of a continuously growing world population, an increasing demand for food and therefore enhanced anthropogenic activities in agriculture. Hence, further research in this field is indispensable.

This study contributes to a better understanding of environmental problems caused by agriculture and aims to deduct financially and environmentally efficient abatement strategies for PM and NH_3. The work has been conducted in the framework of the project “Modelling of sectoral, spatial disaggregated balances of particulate matter (PM) and GHG and assessment of environmental protection strategies at the regional policy level" funded by the German Research Foundation (DFG – Deutsche Forschungsgemeinschaft).

1.2 Problem Statement

Since state of environment and health become an acute problem, many political laws, protocols, and measures (e.g., taxes, emission permits trade) are introduced for the national and international encouragement to perform environment protective actions. Regardless these efforts, environmental pollution continues to rise. Very often, the reason is costly environmental protective services for the majority of small agricultural producers. Although considering growing role of agriculture and presuming that, almost all farmers worldwide could conduct the emission mitigation options, significant abatement results can be expected. In many developed countries, including Germany, regional governments provide financial support to motivate farmers for undertaking environmental protective actions.

Last German emission inventory introduced in the year 2009 is essential contribution to the knowledge about effectiveness of mitigation activity in the country. It is also important to consider an impact of current emission control legislation for successful assessment of cost-effective range of emission reduction measures. However, this inventory neither says anything about economic efficiency of abatement options nor considers political aspects, which are essential for obtaining more precise emission results and making less uncertain projections for the future.

The current work is based on linear optimization modelling approach and addresses analyses of financial and abatement efficiency of environmental protection actions for German individual farms and regions. Moreover, the study suggests cost-effective pollution control strategies. In foreground of this research is the analysis of PM and NH_3 emissions. The choice of PM can be explained by increasing interest to the damaging effect of this pollutant on the environment and human health. Emissions of NH_3 have been analysed in this work, because out of all production sectors agriculture contributes the most to the total NH_3 losses, which, in turn, lead to deteriorations of environmental and health conditions. Moreover, NH_3 released increases PM load through active formation of secondary aerosols.

1.3 Goal and Objectives of the Study

The goal of the current study is, on the one hand, to actualize an existing modelling approach for the economic optimization of the farming activities. In addition, this approach has been developed for investigation of the mitigation and financial effectiveness of PM and NH_3 abatement measures (e.g., through manure spreading with high-precision techniques, filter installation in animal barn, etc.) at the farm and regional level in Germany as a case study. As this approach is already assigned to GHG emission calculations for former studies (see ANGENENDT (2003), KAZENWADEL (1999) and SCHÄFER (2006)), changes in GHG losses resulting must be discussed in this work as a side effect from introduction of PM and NH_3 mitigation options. On the other hand, this study is aimed to analyse an impact of regional environmental legislation and economic feasibility of emission abatement and to propose and prioritise different potential abatement strategies. The objectives of this study are:

1) to investigate the current state of pollution in Germany and to make prognosis for at least 10 years ahead on the basis of optimization modelling approach
2) to assess the mitigation and financial efficiency of various measures for PM and NH_3 abatement at the farm and region level
3) to determine changes in emissions and the effect of uncertain factors' alteration for the economy of individual farms and whole regions; this is to be done in the framework of sensitivity analyses
4) to compare practicability and feasibility of different mitigation options for PM and NH_3 emissions
5) to elaborate emission mitigation scheme, with possible and combinable options for abatement of PM and NH_3 emissions
6) to analyse the interlinkages between NH_3, PM and GHG emissions in the course of mitigation options analysis

1.4 Outline of the Study

Chapter 1 contextualizes the current study, discusses, and justifies its topic and objectives. Chapter 2 presents contemporary state of knowledge about pollutants such as PM and NH_3, including the classification of their sources, discussion of the agricultural sector's contribution to the emissions, analysis of pollutants impact on human and livestock health and environment as well as deduction of possible abatement measures. National and international environmental policy is discussed in Chapter 3. Chapter 4 includes a metadata analysis and general introduction of study sites and specific character of their agricultural sector. Choice of the model is justified in Chapter 5. The same chapter also presents a methodology with related assumptions and all procedures of data collection and information processing. The modelling results are presented for the reference year 2003 and forecasted for 12 years ahead (projection period) in Chapter 6. Thereafter, the impacts of changes in policy conditions, model limitations and emission factors are checked due to the comparison of the reference scenario and prognosis results. Chapter 7 describes different model scenarios and relevant simulations aiming to detect, how PM and NH_3 losses change under certain conditions at the farm and region level. This chapter continues with the presentation of the scenarios' results and further on elaboration of emissions abatement strategy, as a combination of several efficient mitigation options. A general discussion on the emission states, both current and for the prognosis year, as well as the abatement efficiency and uncertainties is carried out in Chapter 8. As conclusion, policy recommendations based on the modelling results are specified (Chapter 9). Literature references, summaries (in English, German), and appendixes complete this manuscript.

2 POLLUTANTS: ORIGINS AND IMPACTS

Due to lack of information, people used to believe that the industry is the only source of major pollutions, and the establishment of environment friendly industrial production will solve the pollution problem and might even stop climate change. However, despite all our attempts to influence the cause of emission in order to reduce pollution, there are still natural emission sources, which are the part of the self-regulatory system of the Earth and can hardly be controlled (UBA, 2005). Therefore, before deciding about relevant mitigation options, particularly in the agriculture, it is necessary to determine the origin of pollutants (natural or anthropogenic), which are to be abated. This chapter provides the insight into character, properties and impact of PM and NH_3 emissions originated from agriculture.

2.1 Particulate Matter (PM) and Ammonia (NH_3): Sources, Climate Impact and Mitigation

Particulate matter and ammonia are pollutants changing the physical and chemical state of the atmosphere, meanwhile affecting the environment and causing climate change both independently and in interactions with each other and other gases. The impact of PM on the environment depends on its fraction size and chemical composition (in the case of aerosols), which in turn is determined by the emission sources. In the atmosphere PM and NH_3 are stemming either directly from natural and anthropogenic sources (e.g., PM from wind erosion and land tillage and NH_3 from manure management in agriculture) or are resulted from chemical reactions between various gases and volatile components suspended in the air (for instance, aerosols or secondary PM). Dominant factors affecting emission intensities, i.e., origin and character of PM and NH_3 losses, are discussed in the following sections.

2.1.1 Particulate Matter

Particulate matter (PM), aerosols or fine particles, are tiny solid or liquid particulates suspended in the air. The particles' size and their chemical composition determine the properties of PM. According to the classification by size, following PM fractions can be defined: superfine (dae[1]< 100 nm), fine (dae < 2.5 µm), rough (dae > 2.5 µm) and coarse (2.5 µm <dae < 10 µm) particles. Larger particles (dae > 10 µm) tend to settle to the ground by gravity, while the smallest particles (dae < 1 µm) can stay in the atmosphere for weeks until they are removed

[1] dae - aerodynamic diameter

by precipitation. Particles can be transported by wind to the distance, which depends on size of PM fraction. Thus, the smaller particles, the longer distance they cover being suspended in the air (UBA, 2005).

Beside PM differentiation by fraction size, particles can also be divided into primary and secondary. Primary PM comes directly from the emission source into the atmosphere. Secondary particles (or aerosols) are the result of chemical reactions of gases and low-volatile products, constituting PM (SPRING *et al.*, 2006).Secondary PM constitutes significant share in total PM, namely about 50-90%. About 50% of aerosols have been detected in the total mass of PM_{10}[2] and $PM_{2.5}$, respectively (ERISMAN *et al.*, 2004).

Two primary fractions - PM_{10} and $PM_{2.5}$ - are investigated in this work. This choice is mainly reasoned by an international concern of health damaging effect of these factions (section 2.2). Moreover, only primary PM emissions are regarded in this study, as consideration of secondary PM requires detailed meteorological information and data on chemical processes, which are far beyond the economic-ecological character of this thesis and its approach.

2.1.1.1 Sources and Levels of PM Emissions

There are diverse sources of air pollution with PM; they can eventually be classified into natural and human/anthropogenic. Naturally occurred primary PM is emitted to the atmosphere in the form of volcano ash, burning products from forest and grassland fires, biologic organic matters (e.g., pollen, spores, microorganisms) from living vegetation, particles from windblown soil erosion, and seas. Natural sources of secondary PM are, e.g., CH_4 from damp regions, nitrous oxide (N_2O) from biological activities in soils, gases out of volcanoes (i.e., NH_3, sulphur dioxide (SO_2), hydrogen sulphide (H_2S), sulphate (SO_4) out of seas and nitrate (NO_3) out of soils and waters (NASA EARTH OBSERVATORY, 2006; UBA, 2005).

The main natural cause of dust in the atmosphere is wind erosion. Depending on meteorological conditions, suspension of soil particles in the air constitute ca. 5-20% of the total PM (UBA, 2005). Wind changes natural surface cover while removing the most fertile portion of the soil from the field. Soil particles stay in the atmosphere causing visibility problems, air and water pollution, reduction in the crops' performance, higher plants' susceptibility to diseases and transmission of plant pathogens (GON *et al.*, 2007).

[2] The definition PM_{10} is used to determine the particulate matter with dae 10 µm, $PM_{2.5}$ is the particulate matter with dae 2.5 µm.

Among anthropogenic sources of primary and secondary particles we can distinguish: combustors for energy supply (e.g., power stations), waste burning facilities, combustion processes in agriculture, domestic fuel (i.e., gas, oil, and coal), industrial processes (for instance, metal production), construction sites, handling of bulk materials and agricultural operations (NASA EARTH OBSERVATORY, 2006; UBA, 2005).

Considering initially natural cause of wind erosion, it is important to mention that its intensity and resulting PM atmospheric load are often deteriorated under the influence of anthropogenic factors. For instance, the problem of wind erosion becomes more acute on the background of improper land management. The direct dust release from arable land due to tillage is generally much higher than dust emission from wind erosion (FUNK *et al.*, 2007a). Atmospheric conditions and soil properties determine the intensity of PM emissions from tillage operations, e.g., in rainy seasons the emission is clearly much lower than in dry periods. The results of experiments conducted by FUNK *et al.* (2007a) showed higher emissions by sandy than clay soils (by the same soil moisture). Beside soil properties, another factor affecting dust release from agricultural soils is the type of tillage operation employed. For instance, ploughing causes much higher PM emissions than land cultivation through harrowing or disking (FUNK *et al.*, 2007a). Nevertheless, relatively high humidity eliminates the discrepancy between PM emissions from various land cultivation operations due to low PM emission potential (ÖTTL *et al.*, 2007).

Combustion in agriculture is generally used by farmers either to prevent unwanted weeds or to prepare an area (through removal of shrubs and trees) for livestock pastures and/or arable production. Burning in agriculture releases into the atmosphere a wide variety of pollutants (e.g., carbon monoxide (CO), CO_2 and soot), which become airborne and are generally transported downwind (FUNK *et al.*, 2007a). Another negative side-effect of agricultural burning is the loss of organic matter, which leads to the soil degradation (USDA, 2006; UBA, 2005). Agricultural combustion is still practised in several countries, where environmental pollution is not a “number-one-concern” (e.g., USA and Russia). In Germany, however, agricultural burning has been banned by the environmental law (WEGENER *et al.*, 2006).

In animal husbandry, PM emitted from animals per se (e.g., skin, hairs, and faeces) can be considered as naturally originated, but PM emissions stemming from fodder and litter preparation as well as from barn cleaning rank among anthropogenic activities. Particles stemming from livestock management by up to 85% consist of organic material carrying gases, microorganisms, endotoxins[3], and odours. Dust from animal husbandry is primarily emitted from animal fodder (ca. 90%), bedding materials (55-68%), animal bodies (up to 12%) and faeces (ca. 8%). Although these values may differ depending on animal type (HARTUNG *et al.*, 2007). Thus, if in poultry houses dust mainly originates from feathers and manure, and less from feed, bedding material, micro-organisms, and fungi, PM in pig houses primarily stems from feed, skin particles and faeces and less from bedding material (AARNINK *et al.*, 2007). Moreover, PM composition varies depending on animal type and housing system. For instance, the highest amount of protein and microorganisms was detected in poultry houses; there the concentration of bacteria was higher in aviary than in cage system. The highest concentration of antibiotic residues was found in pig houses (HARTUNG *et al.*, 2007).

The concentrations of inhalable and respirable dust are also different for various animal types. The highest PM concentration during 24 hours was detected in poultry houses (ca. 10 and 1.2 mg m^{-3} of inhalable and respirable dust, respectively), followed by pig barns (about 5.5 and 0.46 mg m^{-3} of inhalable and respirable dust, correspondingly) and cattle houses (nearly 1.22 and 0.17 mg m^{-3} of inhalable and respirable dust, respectively) (SEEDORF *et al.*, 2000).

Concentrations and, consequently, emissions of PM in livestock barns depend on following interrelated factors: animal type, age and activity, housing system, duration of a housing period, ventilation rate, seasonal changes, and farm management. Constructions, ventilation, heating, and farm management vary from barn to barn and affect PM concentration; hence, it is lower by a higher ventilation rate (NANNEN *et al.*, 2007). An increasing animal activity causes a raise in concentration of PM with dae higher than 2 µm (METHLING *et al.*, 2002). Farm management and animal activities are connected in a way that, for instance, animals feeding boost up animal activities, which in turn enhance dust concentration (mainly of PM with dae >= 10 µm) in the livestock house. Seasonal changes also affect PM emissions from animal barn. Thus, dust emission in summer is higher than in winter due to a higher air volume flow (NANNEN *et al.*, 2007).

[3] Endotoxins are constitutes of the bacteria's' cell wall, which are released after the decay of the bacteria's. Endotoxins are one of many inflammatory substances (AGENTUR FÜR ERNEUERBARE ENERGIEN, 2009).

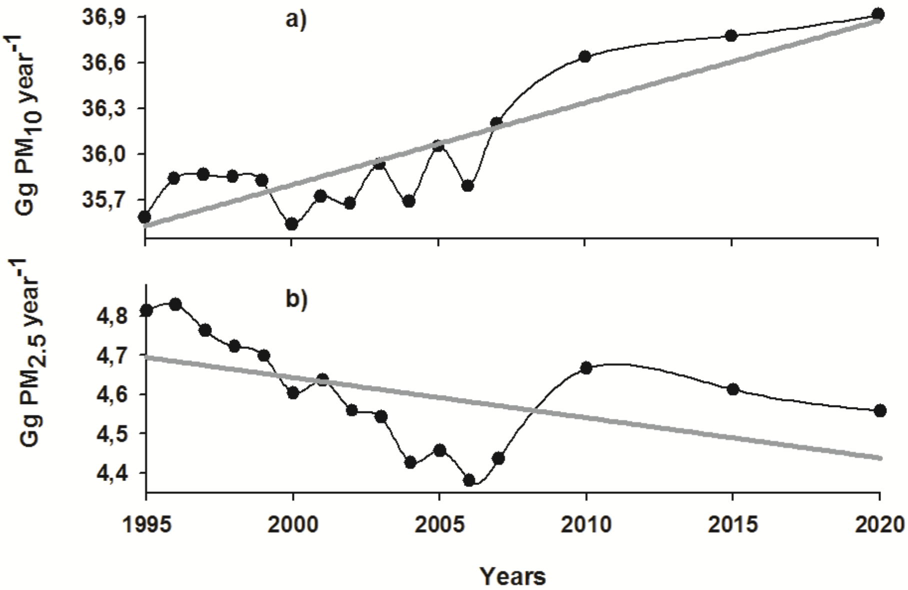


Figure 1 PM_{10} (a) and $PM_{2.5}$ (b) emissions from the German agriculture between 1995 and 2007 and prognoses for 2010–2020

Source: UBA (2009b)

According to UBA (2005) and SPRING *et al.* (2006) the contribution of agriculture into cumulative PM emission is about 9% for PM_{10} and 7% for $PM_{2.5}$, primarily through natural processes.

Figure 1 shows the development of the cumulative $PM_{10}/_{2.5}$ from agriculture in Germany between 1995 and 2007 and prognoses for PM emissions in 2010-2020. Losses of PM_{10} from agriculture rose from 1995 till 2007 by 2%, by 0.05 Gg[4] year^{-1}, while $PM_{2.5}$ emissions declined by 8%, with 0.03 Gg per year (UBA, 2009b). According to the prognosis 2010-2020, PM_{10} emission will tend to rise although with a lower annual growth ratio (i.e., about +0.08% comparing to +0.14% for the period 1995-2007). Although the average of $PM_{2.5}$ emission forecasted for 2010-2020 is slightly higher (by +0.2%) than the average value for the period 1995-2007, $PM_{2.5}$ emission tends to decline with the yearly rate of ca. –0.24% versus –0.65% between 1995 and 2007. However, UBA (2009b) does not provide any explanation, why foreseen trend is increasing for PM_{10} and decreasing for $PM_{2.5}$ emissions.

Another projection of PM emission for 2010-2020 from JÖRß *et al.*, (2007) shows constant development over the forecasted period. Thus, according to the prognosis the amount PM_{10} released in 2010-2020 comparing to 1995 has to increase by +0.3%, while for $PM_{2.5}$ emissions the decline by more than –0.6% is expected. In contrast to the year 2007, the change of forecasted emission equate to +0.4% and –0.8% for PM_{10} and $PM_{2.5}$, correspondingly.

[4] Gg – gigagram equivalent to kilotonne (kt)

Major part of PM_{10} emitted is stemming from agricultural soils (over 50%) and manure management (ca. 48%) (UBA, 2009b). According to UNECE (2009a) 32% and 57% of PM_{10} and 35% and 45% of $PM_{2.5}$ emissions from animal husbandry stem from pig and poultry houses, respectively. Thus, it has been estimated that livestock management produces 9-35% of total PM_{10}.

2.1.1.2 Impact of PM on Climate

After being emitted to the atmosphere, primary PM stays suspended in the air, meanwhile reacting with atmospheric gases. The speed of chemical reactions of PM in the air depends on weather conditions (temperature, moisture, and electricity) and properties of particles (size and composition), etc.

Fast formed secondary particles directly affect environment through either scattering or absorbing of solar and terrestrial radiation. This, in turn, changes cloud formation and atmospheric temperature (NASA EARTH OBSERVATORY, 2006). Aerosols serve as a basis for formation of cloud droplets. Concentration of secondary PM increases within a cloud, and modulates cloud properties, frequency of cloud occurrence, cloud thickness, rainfall amounts and intensity of sunlight reflection. Smaller aerosol droplets stay longer in the atmosphere, while larger ones sediment faster as a rainfall (GRID-ARENDAL, 2001).

In addition, the major aerosols have a "direct” cooling effect through sunlight reflection. However, there are secondary particles yielding large positive radiative forcing and thus, producing warming effects (KLOSTER *et al.*, 2008; GRID-ARENDAL, 2001). Decreasing or increasing of atmospheric temperature results from combination of both effects. However, it is not only aerosols properties influencing climate change, they rather work in association with other external factors such as changes in the atmospheric composition, alteration of surface reflectance by land use, and variation in the sun radiation (NASA EARTH OBSERVATORY, 2006).

Both primary and secondary PM combined with other gases and chemical elements suspended in the air, are the main precursors of smog and acid rain, which are harmful for any living being (NASA EARTH OBSERVATORY, 2006).

The transboundary character of PM emission atmospheric transport has become evident. Thus, according to UN (2006), an average for Europe modelled transboundary contribution of $PM_{2.5}$ and PM_{10} constituted about 60% and 25%, respectively. However, it is important to mention that the application of PM mitigation measures locally seems to be more efficient rather than conducting abatement actions after particles are already spread in the atmosphere. There, due to the chemical processes, PM is converted into easily changeable and hence more difficult to neutralize aerosols. Additionally, spatial distribution of PM_{10} supports a regional character on emission distribution, as coarse material sediments relatively rapidly and a fine dust tends to stagnate in the atmosphere, especially by low wind speed. Therefore, PM of various fractions is mainly deposited locally, e.g., due to fog or/and rainfall events. This suggests that major PM emission mitigation plans need to take a regional approach (PUN *et al.*, 1999).

2.1.1.3 Mitigation of PM Emissions

Proper feeding management and sprinkling of oil-water suspension in animal barns are some measures preventing high PM emission. Although AARNINK *et al.* (2007) proposed that PM losses from dry feeding is as high as from liquid feeding, the majority of studies state that wet feeding causes comparatively lower PM emissions (UNECE, 2009a; METHLING *et al.*, 2002). Humidification of hay, with high airborne organic dust emission potential, is an efficient measure for reduction of PM losses from horse management. Thus, the use of silage/haylage instead of dry hay and immersion of hay in the water for 30 minutes before animals feeding reduce released respirable dust by up to 30-90% (CLEMENTS *et al.*, 2007; GIRARD *et al.*, 2009).

Several studies disagree about PM abatement potential of fat addition into animal fodder suggesting PM reduction from 10% to 100% (AARNINK *et al.*, 2007). Regardless the mitigation efficiency of this measure, its application is limited due to a negative impact on meat quality, particularly by fattened pigs. Thus, fraction of soy bean and the rapeseed oil in the feeding mixture should not exceed 1-1.5% and 2-3%, respectively (WEIß *et al.*, 2005).

The form of provided fodder (e.g., meal or pallets) plays an important role for PM emissions from animal feeding. Thus, the change from meal to pallets feeding reduces PM emissions by over 30%. Moreover, type of fodder ingredients determines the intensity of dust release from pig feeding. For instance, fodder components such as wheat, sorghum, and barley generate higher PM emission than corn (AARNINK *et al.*, 2007).

Besides feeding management, PM emission in barn depends on type of bedding material. For instance, it is higher by peat than by straw bedding (JEPPSSON, 1999). However, the origin of straw for bedding material has diverse impact on the PM losses: flax straw causes less dust emission than “wheat, barley, rye, and hemp straw”. Moreover, the more humid straw bed, the less PM is released from it (AARNINK *et al.*, 2007).

Spraying of oil-water emulsion in pig houses has been proposed by TAKAI (2007) as an alternative for PM abatement. However, application rate must be at least 7 ml m^{-2} day^{-1} and oil concentration in oil-water suspension no less than 20% in order to assure effective PM mitigation oil. The reduction of airborne PM in barn air with this technique is limited due to high amount of water required and due to side effects as diffusion, electro static charge, turbulence, and uneven distribution of dust particles in animal house.

To the end-of-pipe technologies of PM abatement applicable in animal barns belong filters. It has been demonstrated that already the use of filters for removal of coarse airborne dust from animal barn improves air quality and hence fattened pig performance (HARTUNG *et al.*, 2007). The separation of PM from the exhaust air is assured through the physical and biological cleaning principles. The physical separation of the dust implies moisturising of air, leading it through the filtering media and accumulating of smaller PM fractions into bigger dust particles. These particles sediment on the filtering material to be later washed out as into the sump (SCHIER, 2005; KTBL, 2008b). The biological degradation of dust particles by the microorganisms on the filter media guarantees removing of organic PM from the exhaust air (KTBL, 2008b). Exhaust air treatment systems (EATSs), such as trickling bed reactors, chemical and biological scrubbers, assure emission reduction of the total dust by 70-90%. A know-how like electrostatic filters may reduce PM_{10} emissions from the laying hens’ houses by 70-80%, although they must be better developed for being installed in animal houses (MITCHELL *et al.*, 2007). Filters in animal barns are not considered as BATs in the EU because of their high costs, ecological threats resulted from chemicals application and their discharge with filter wastewater, and also due to unstable air cleaning performance (KTBL, 2008b; MELSE *et al.*, 2009b). Nevertheless, above-mentioned emission abatement efficiency of filters suggests that cleaning of exhaust air is very important to comply with current and future PM_{10} and $PM_{2.5}$ emission thresholds (UNECE, 2009a; AARNINK *et al.*, 2007; MELSE *et al.*, 2008).

The abatement of dust caused by land cultivation can be achieved either through reduction of surface wind speed or increase of soil resistance. Thus, planting of shelterbelts reduces wind speed over field surfaces, and therefore, relatively less amount of PM released due to tillage operation is blown away. However, this technique can be regarded as supportive due to its relatively high costs and requirements of long term maintenance (FUNK *et al.*, 2007b). Another option to reduce PM emissions from tillage practises is application of land preparation techniques causing less soil disturbance. Hence, remaining yield residues on field and application of reduced tillage or no-tillage lead to significant reduction of soil loss ratio (by up to 100%). Moreover, beside decrease of soil loss, reduced tillage or conservation tillage aims to protect biodiversity, preserve soil moisture, cut off air pollution (not only in terms of PM, but also CO_2 an SO_2) and appears as an landscape forming factor (KERTÉSZ *et al.*, 2010; PUTTE *et al.*, 2010; DUXBURY, 1994; FUNK *et al.*, 2007b; GAMBA *et al.*, 2004). Nevertheless, multiple studies report negative side effects of reduced tillage such as possible yield reduction in short term (by up to 30%) by various crops and soil types and qualities. Beyond this, type of tillage technique determines yield reduction, as yield and tillage depth are negatively related. Thus, the yield from no-tillage can be lower than one from reduced tillage due to a worse soil-seed contact, soil water drainage, roots aeration, etc. (PUTTE *et al.*, 2010; SILVA *et al.*, 2010).

Taking into account dependency of PM emission from soil tillage on weather conditions it can be advised to conduct tillage operations on humid soils, or at high air humidity, e.g., in morning hours or after small rain (especially relevant for sandy soils[5]) in order to reduce dust emissions from land preparation.

2.1.2 Ammonia

Ammonia (NH_3) is a "colourless gas, very pungent odour", "much lighter than the air" and extremely good soluble in water (WIBERG *et al.*, 2001; PERRY *et al.*, 1995). In nature, NH_3 results from biosynthesis, when it is produced within nitrogen (N) fixation process. In the atmosphere NH_3 is a potential basis for aerosols development due to its reaction with other atmospheric elements like sulphur oxides (SO_2, SO_3) and nitrogen oxides (NO, N_2O), non-methane volatile organic components (NMVOC), and other particulates suspended in the air (DEFRA, 2002; SPRING *et al.*, 2006; RENNER *et al.*, 2007; SCHNELLE-KREIS *et al.*, 2007). Resulting aerosols (section 2.1.1) , e.g., ammonia sulphate and ammonia nitrate, are easily breakable and transferable back to NH_3 (DEFRA, 2002).

Regardless the fate of NH_3 emissions in terms of secondary PM formation, this study is concentrated on NH_3 losses before the formation of secondary aerosols.

[5] Personal communication of Susanne Wagner, University of Stuttgart, and Roger Funk, ZALF, from 23.01.2008

2.1.2.1 Sources and Levels of NH_3 Emissions

Most of gaseous losses of N constitute NH_3 emissions. Agriculture and particularly livestock farming contributes ca. 80-90% to NH_3 losses in Europe. Ammonia in animal husbandry results from microbial decomposition of nitrogenous compounds (DEFRA, 2002). Nitrogen excreted in form of urea in urine and undigested proteins in faeces contributes 70% and 30% to the total N excreted by cows and pigs, respectively. However, these values can vary considerably depending on animal performance, fodder, housing system, manure properties and other factors (PRATT *et al.*, 2004).

Under the influence of ambient temperature and manure pH ammonium (NH_4) in manure or litter is easy balancing between the liquid and gas phases before being emitted to the atmosphere as NH_3. When manure pH is below 7, nearly all NH_3 exists in a non-volatile form, i.e., NH_4. By relatively higher temperatures NH_4 brakes down into highly volatile NH_3 (MEISINGER *et al.*, 2000).

Several factors on each stage of manure management affect NH_3 losses. Emissions of NH_3 from livestock housing losses depend on barn design (e.g., ventilation system and barn floor design), manure properties, animal types, frequency of manure removal from the barn, etc. Ventilation rate, ventilation system, and positioning of inlet and outlet openings determine the airflow pattern. The airflow rate affects temperature and velocity of the air above the manure surface; its increase may result in higher NH_3 concentrations and thereafter, emissions (FERM *et al.*, 2005; KOERKAMP *et al.*, 1998; SAHA *et al.*, 2010).

Manure removal out of animal barn is an implicit part of the common farming techniques, but frequencies of removal vary depending on livestock type. Thus, cattle solid manure is generally removed from barn daily (UNECE, 2007). In poultry houses with manure-belt, excreta are not allowed to build up over time due to high possibility of damaging the entire manure-removal system[6]. Hence, poultry dung is generally removed 1-2 times per week (varying from farm to farm). In hens' houses with deep pit for manure storage, as well as in broiler houses with deep litter, removal of litter and excreta occurs principally once per year (BRADE *et al.*, 2008).

In general manure is transported from animal houses into specially assigned storage confinements, where NH_3 emissions and N-leaching should be prevented (BMJ, 2007). Alternatively, manure can be used in biogas production plant. However, the potential of NH_3 losses is higher

[6] Personal communication from 06.10.09 with Prof. Dr. Werner Bessei, Institute for Farm Animal Ethology and Poultry Production, University of Hohenheim

due to anaerobic digestion of the slurry in biogas-tanks, its higher pH and TAN[7] concentration (SOMMER, 1997). Biogas production reduces total GHG emissions, where 44%, 48%, and 8% are attributed to the reduction of CO_2, CH_4, and N_2O losses, respectively (NIELSEN *et al.*, 2004).

On the stage of manure storage, NH_3 emissions depend on animal category and breed, weather conditions (i.e., ambient air temperature, humidity and wind), manure characteristics (e.g., dry matter content, temperature, and pH), size of manure surface, storage duration, and preceding housing technique (BERG *et al.*, 2003). Thus, manure from pig and cattle barns with deep litter has a higher dry matter content and emits more NH_3 than dung from animal houses with less or even no straw (MEISINGER *et al.*, 2000; BERG *et al.*, 2003).

From the point of manure land application, it can be differentiated between NH_3 losses during and after spreading procedure. The volatilization of NH_3 during manure spreading is estimated as a bit higher than 1%. However, the highest rate of NH_3 loss of around 40-70% occurs in several hours after manure land application (MEISINGER *et al.*, 2000; UNECE, 2007).

Factors such as manure dry matter content, soil condition (e.g., moisture, pH content, cation exchange capacity (CEC), and infiltration rate), manure land application method used, and weather conditions (e.g., temperature, wind speed, and rainfalls) have potentially significant impact on NH_3 losses from manure land application (BRASCHKAT *et al.*, 1996; MEISINGER *et al.*, 2000). For instance, every increase of dry matter content of cattle and pig manure by 1% is associated with the raise of NH_3 losses from manure land application by ca. 5% (DEFRA, 2002).

Ammonia losses from pasture depend a lot on N-repletion of soil and thus N-concentration in the grass. Oversaturation of soil and plants with N causes higher amount of N excreted with urea of the grazing livestock. This, in turn results in a higher NH_3 emission potential (DEFRA, 2002).

The content of easily acceptable by plants N per mass unit of mineral fertilizers is higher comparing to animal excreta. By this reason, 1 kg of N is cheaper for mineral fertilizers. Due to their higher N-content mineral N-fertilizers have to be applied onto the land very carefully, as their application has greater danger of N leaching and therefore of increasing NH_3 emissions. Additionally, NH_3 losses depend on the form of mineral fertilizers (i.e., liquid or solid) applied. Emissions of N_2O and NH_3 are lower by liquid mineral fertilizers infiltrating faster into the soil. Opposite is the emission situation by solid mineral fertilizers generally broad-

[7] Total ammoniacal nitrogen (TAN = NH_4-N (ammonium nitrogen) + NH_3-N (ammonia nitrogen))

casted onto agricultural land and not always incorporated into the land shortly after spreading. For instance, NH_3 losses from urea granulates is much higher than the emission from liquid urea (by 27% of NH_3-N) (KUCEY, 1988). In addition, NH_3 emission depends on the type of mineral fertilizer: urea causes much higher NH_3 losses than calcium ammonia nitrate (DÄMMGEN *et al.*, 2009). Weather and soil conditions (e.g., moisture and temperature) assure additional impact on amount of NH_3 released due to mineral fertilizers land application. For instance, wind, low soil moisture and temperature coincide to relatively higher NH_3 emissions (PALMA *et al.*, 1998).

In general, ca. 95% of total NH_3 is released from German agriculture. Major part of these losses stem from cattle farming (49%), particularly from managing dairy livestock. Pig husbandry takes the second place for the amount of emitted NH_3 (23%). Poultry contribution to the total NH_3 losses from German agriculture is only 9%. Non-animal agricultural, such as use of fertilizer, is responsible for 14% of NH_3 losses. Absolute values for NH_3 emissions from German agriculture in 2007 are presented in Figure 2.

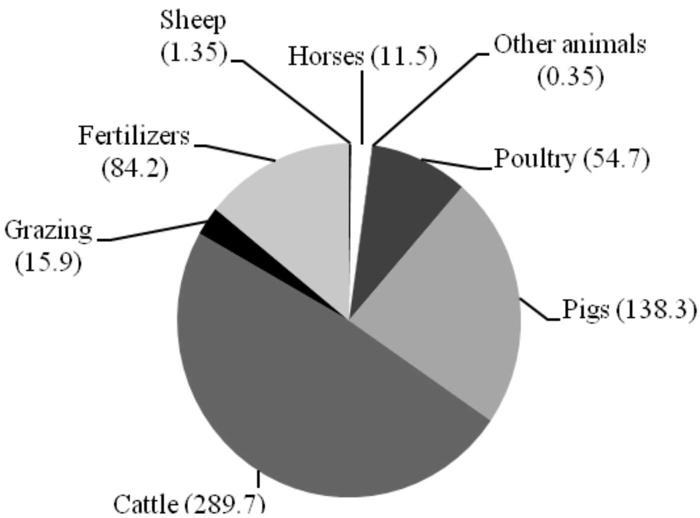


Figure 2 NH_3 emissions from agriculture in Germany for the year 2007, Gg NH_3 $year^{-1}$

Source: UBA (2009a)

Partial NH_3 emissions[8] from livestock production such as handling of manure in animal houses, its storage in special capacities (ca. 50% of total NH_3) and manure land application (42% of total NH_3) constitute the major NH_3 emission. The contribution of grazing is only about 9% (DÄMMGEN *et al.*, 2009).

[8] Partial NH_3 emissions are emissions occurred due to the performance of different agricultural activities, like handling of manure in animal barn, manure storage and manure land application, animal grazing. The total NH_3 emission is the sum of several partial NH_3 emissions.

In Germany, between 1991 and 2007, no significant fluctuations have been observed in the development of NH_3 emissions, and NH_3 losses levelled out at about 624.4 Gg (WAGNER *et al.*, 2009). According to UBA (2009a), the NH_3 emission in Germany in 2010 still overcome the ceiling established by the Gothenburg protocol for the year 2010, namely 550 kt, by 54 kt or ca. 9.8%. Although the NH_3 emission threshold 2020 for Germany has been set 0.8% higher than the respective data for 2010, the emission ceiling for 2020 (566 kt) would still overcome estimated emission values by ca. 7.6% or 43 kt (AMANN *et al.*, 2008; UBA, 2009b).

2.1.2.2 Impact of NH_3 Emission on the Environment

Many environmental problems as total acidification and eutrophication[9] are caused by NH_3 deposited from the atmosphere onto water and soil and that is why the topic of NH_3 emission is very crucial for agriculture (DEFRA, 2002).

Secondary PM, to which formation NH_3 contributes, is generally removed from the atmosphere with the rainfall often causing acid rains (FERM *et al.*, 2005; KOERKAMP *et al.*, 1998; MILES *et al.*, 2004). In addition, ammonium salts, i.e., ammonium sulphate and ammonium nitrate, neutralize acids in the atmosphere and NH_3 accelerate the processes. However, ammonium salts are easily breakable and transferable back to NH_3 (DEFRA, 2002; KOERKAMP *et al.*, 1998).

Both a short lifetime of NH_3 and its uneven distribution in the atmosphere cause large variations in NH_3 deposition. Ammonia emission has a local character, but it can be changed by several meteorological factors. Thus, rain and wind transport NH_3 over long distances creating interregional damage (HEALTH CANADA, 2006).

Damages caused by NH_3 are generally noticeable only after long time. For instance, soils exhaust its ability to neutralize N-based acids only over decades. Moreover, in medium and long term, N-overenrichment of soil may lead to the replacement of valuable plants with weeds (KOERKAMP *et al.*, 1998; DEFRA, 2002). The fact that consequences of NH_3 emissions become obvious only after a while, does not mean that there is a lot of time before any of mitigation options to minimize NH_3 losses is undertaken. The earlier we start applying the measures to prevent NH_3 emissions, the higher are the chances to protect our future environment from excess of NH_3 and its results.

[9] Eutrophication is a natural process, in which enrichment of water bodies with nutrients stimulates algal growth and accumulation of organic matter (FERREIRA *et al.*, 2007; KOTTA *et al.*, 2009), causing air and water pollution.

2.1.2.3 Mitigation of NH_3 Emission

Options for NH_3 reductions on different stages of livestock production and manure management are independent but not just additive in terms of their emission reduction. Therefore, to be able to observe the efficiency of specific abatement strategy, a complete NH_3-production chain has to be taken into account. For instance, NH_3 losses from housing and manure management vary between systems with liquid and solid manure; however their cumulative NH_3 emission reduction is similar (BERG *et al.*, 2003). It is important to consider mitigation practises for NH_3 in interlinkages with PM and GHGs, because NH_3 contributes to the formation of secondary PM and has some common with GHGs sources in agriculture (BRINK *et al.*, 2005; MONTENY *et al.*, 2006).

The abatement of NH_3 losses from grazing animals implies operation of rotational rather than of continuous grazing. In addition, shortage of grazing season leads to reduction of N_2O losses. However, the emission reductions greatly depend on the character of faeces distribution and soil and weather conditions (BUSSINK *et al.*, 1998; CHADWICK *et al.*, 2004).

The main principles for abatement of NH_3 in animal houses are the improvement of barn ventilation, employment of EATS, the reduction of the manure surface area and changing of manure properties, application of a bedding material, adjustment of animal feeding management, and frequent slurry removal from animal barn to external storage capacities.

Inner environment of the livestock house, where the concentration of NH_3 and other gases is high, can hardly be controlled effectively only through conventional roof ventilation especially during the winter, when ventilation rate is quite low. In this situation employment of a partial ventilation system, e.g., at the pit, reduces more efficiently a concentration of NH_3 in the air above the liquid manure surface (SAHA *et al.*, 2010). High rates of forced ventilation drying the dung collected on the belts in poultry battery houses lead to the reduction of the poultry manure moisture and hence of NH_3 losses (FERM *et al.*, 2005). In pig houses, higher ventilation rates decrease the effect of rising outside temperatures on the internal NH_3 concentrations. However, higher ventilation rates also have side effects: beside boosting electricity costs they increase an air velocity above manure surface, enhance NH_3 evaporation, and provoke dust emission (FERM *et al.*, 2005; UNECE, 2007).

Two factors affecting NH_3 losses, i.e., exhaust airflow rate and concentration, can potentially be influenced to reduce NH_3 emissions. However, changing of the flow rate is restricted through the requirements to livestock well-being (JANSSEN *et al.*, 1990). Thus, only the reduction of exhaust airflow concentration can be regarded as possible NH_3 abatement option. In this concern, it is important to mention EATS. Their installation is only plausible in the animal barns with forced ventilation (HAHNE *et al.*, 2007). Biofilters do not suite for the reduction of NH_3, which, however, can be removed from the exhaust air with trickle bed reactor and chemical washers. Trickle bed reactors reduce NH_3 (by 70-90%) through its oxidation into nitrite and nitrate and their later discharged with the wastewater (KTBL, 2008b; SCHIER, 2005; MELSE *et al.*, 2009c; SHERIDAN *et al.*, 2002; MELSE *et al.*, 2009a). Chemical scrubbers abate NH_3 emissions by ca. 95% converting gaseous NH_3 into acid liquid, and after the reaction with sulphuric acid into NH_3 salt solution, which is eventually discharged (SCHIER, 2005; MELSE *et al.*, 2009c; SHERIDAN *et al.*, 2002; MELSE *et al.*, 2009a; KTBL, 2008b). Beside single stage filters there are multi-pollutant filters, e.g., 2- and 3-stage EATS, where the stages can be combined together in several ways. The higher the number of cleaning steps in the filter, the more pollutants can be abated and the more efficient is the emissions reduction. Nevertheless, the multi-pollutant scrubbers are still running as experimental systems employed at several farms in different countries (e.g., the Netherlands, Germany, and Denmark) (SCHIER, 2005; MELSE *et al.*, 2009c).

Application of the EATS for the separation of CH_4 is restricted by the low solubility of CH_4. However, significant removal of CH_4 from the exhaust air might be achieved at a relatively high dwell time of air in the filter media. Some N_2O can be emitted as the side effect of denitrification and nitrification processes in the biotrickling filter. Although employment of the EATS is costly, the filters appear to be a very perspective NH_3 abatement technique due to its high mitigation potential (MELSE *et al.*, 2009a).

Reduction of the manure surface is another important way to decline in NH_3 losses. It can be achieved throughout the use of manure pans, gutters or/and small channels, a frequent removal of manure from the barn floor with toothed scraper running over a slatted floor (e.g., in cattle barn) or flashing of the barn floor with water. However, flashing of excreta from the floor can cause more problems with animal slipping, raise of odour emissions and results in ca. 50% higher slurry volume, that requires larger storage facilities (OOSTHOEK *et al.*, 1990; UNECE, 2007).

Changing properties of manure stored underneath the barn floor (e.g., in pig houses with fully or partially slatted barn floor) through the reduction of manure and urine pH, manure dry matter content and temperature leads to the significant reduction NH_3 losses from animal house (MULVANEY *et al.*, 2008; UNECE, 2007; PRATT *et al.*, 2004). Manure cooling can be achieved through the increasing depth of manure pit or installation of groundwater system, what is not always possible and quite costly (UNECE, 2007). Mechanical separation or anaerobic digestion assures NH_3 abatement by 50%. Disadvantages of this method are an increase in NH_3 emission due to extended storage periods of the solid material, higher NH_3 losses occurring due to manure spreading and excessive capital and operational costs (O'SHEA *et al.*, 2009; UNECE, 2007; METHLING *et al.*, 2002; AMON *et al.*, 2004). Although anaerobic digestion of slurry causes decrease of NH_3 and CH_4 emissions (by ca. 70%) and raise of N_2O losses (by over 30%), the net total GHG emission cuts off by nearly 60% (AMON *et al.*, 2006). An addition to the slurry of organic acids (e.g., lactic) or inorganic (e.g., nitric and sulphuric) acids or a transparent and odourless TiO_2 liquid solution) reduces pH up to 6-6.5. Emissions of NH_3 and CH_4 losses are minimal at this pH value of slurry. Thus, treatment of slurry with acids assures eightfold reduction of NH_3 emissions comparing to untreated liquid manure. Additional mixing of manure leads to 60 times higher reduction of NH_3 released. However, organic acids are not so efficient, because they are degrading rapidly and large quantities of them are required and inorganic acids cause overfertilization with S or P. Moreover, acids handling on the farm can be hazardous, and slurry treated with acids is to be applied onto the land with a high caution (UNECE, 2007; MARCELLA *et al.*, 2007; OOSTHOEK *et al.*, 1990; DÖHLER, 1990; MONTENY *et al.*, 2004; BERG *et al.*, 2004).

The choice of bedding material allows controlling NH_3 emissions. Different types of peat adsorb ca. 0.3 – 2.7% NH_3 per dry matter weight of litter material, while barley straw absorbs only 0.8%, oat straw 0.5% and 0.7% for long and chopped, respectively, wood shavings 0.8% and sawdust 0.6% of NH_3. Peat-straw chopped mixture reduces NH_3 losses by nearly 57% comparing to the long straw bedding. Although peat has high NH_3 emission abatement potential due to a relatively low pH (nearly 3.0-4.5), high C/N ratio (about 91) and high water absorbing capacities (JEPPSSON, 1999), its application leads to a higher amount of PM released (section 2.1.1).

Not only type but also amount of litter in the animal house has a significant impact on NH_3 losses. Thus, comparing to slurry-based system, ca. 33% and 100% more straw for cattle and pig house, respectively assures NH_3 emission reduction of 50% and 18%, correspondingly (GILHESPY *et al.*, 2009). Nevertheless, regardless a positive control of temperature by animals themselves and hence a lower energy demand for ventilation and heating, there are some drawbacks. Among them are increasing N-content of manure and extra costs for straw supply and handling (UNECE, 2007). Moreover, if a change from straw-based to the slurry-based housing system result in lower N_2O (by 2-5%) and CH_4 (by 6-8%) losses, it causes a boost of NH_3 emissions (AMON *et al.*, 2001; MONTENY *et al.*, 2006; CHADWICK *et al.*, 2004).

The adaptation of the diet is another alternative for reduction of NH_3 released from animal husbandry. For instance, an adjustment of fodder nutrient intake through the addition of benzoic acid or minerals like Zn, Cu, Mg, and Mn into poultry diet slows down the process of turning uric acid in poultry excreta into NH_3 (KIM *et al.*, 2003, 2004).

It is known that protein in animal faeces is a potential source of NH_3 emission. Only about 20-40% of the protein-N from livestock diet is found in animal and their products (meat, eggs, milk, etc.), but the rest 80-60% of protein-N is excreted (DEFRA, 2002). From this perspective an optimisation of the crude protein (CP) level in livestock diets is regarded as a good method for reduction NH_3 emission from animal husbandry (KIRCHGEßNER, 2004; POWERS *et al.*, 2007). Reduction of CP, e.g. by 70%, may lead to about 30%-reduction of N in excreta, comparing to the manure excreted by animals on a standard diet (DEFRA, 2002). However, the ratio, by which NH_3 emission can be reduced, is determined by the regional reference feeding practises (without abatement attempts), dietary composition livestock fodder and animal physiology (UNECE, 2007). Optimal CP-level in animal diet as well as its improved digestion can also be obtained through the introduction of phase feeding, e.g., by fattened pigs. This practise implies a gradual reduction of a general protein-N level and allows dietary crude protein reduction by ca. 40% and hence NH_3 emissions abatement by nearly 62.4% (HAYES *et al.*, 2004a). Regardless that CP-adjusted feeding assures reduction in NH_3 and N_2O losses (by 10-30%) (BRINK *et al.*, 2005; MONTENY *et al.*, 2006), it may result in a higher amount of CH_4 and N_2O released during manure storage and after manure land application (MELSE *et al.*, 2009a). Beside emission reductions, adjusted livestock diets affect animal performance. In order to assure a positive impact, a right balancing of nutrients in livestock diets is crucial (SINCLAIR *et al.*, 2001; TOUCHETTE *et al.*, 1998; KIM *et al.*, 2009; MELUZZI *et al.*, 2001). KIM. *et al.* (2004) states, that an inclusion of ZnO into broilers' diets shows relatively higher performance. Also HAYES *et al.* (2004a) found that finishing pig average daily gain changed only minimally due to the decrease of the dietary protein up to 13%, under the condition of addition to the ration of synthetic amino acids. According to KIRCHGEßNER (2004), another advantage of feeding pigs with protein-reduced fodder is a lower intake of drinking water by pigs and thereafter less slurry produced and stored. This is a precondition for a significant NH_3 emission reduction. Moreover, costs of manure land application decrease with to the reduction of slurry amount.

Application of NH_3 emission reducing techniques in animal house can be restricted due to high costs of structural adjustments in animal barn and increasing energy requirements

(StMELF Bayern, 2003; Kim *et al.*, 2004). Thus, it is important to move manure from animal barn into specially adjusted storage confinements to assure a higher NH_3 mitigation comparing to manure storage in a livestock house (StMELF Bayern, 2003).

Well organized manure storage may lead to the reduction of NH_3 emission by nearly 80% and abatement of CH_4 and N_2O by ca. 90% and 99%, respectively (Brink *et al.*, 2005; Monteny *et al.*, 2006). Natural crust formation is the least cost intensive way to abate NH_3 losses from the stored liquid manure. However, if natural crust appears relatively rapidly by cattle slurry (in 4-6 weeks), it often does not appear on the surface of stored pig liquid manure due to its very low viscosity. Beside this, crust does not develop for (anaerobically) digested slurry in biogas tanks (Sommer, 1997; Döhler *et al.*, 2002; Schäfer, 2006; Amon *et al.*, 2005). Also encrustation of the stored slurry surface results in increasing N_2O emissions (Berg *et al.*, 2004). Generally natural crust formation technique for NH_3 abatement could be taken into practise by farms, where liquid manure is added into tanks from its bottom and where slurry is not spread frequently and natural crust is rarely disturbed (UNECE, 2007). The latter is not always the case and introduction of slurry containers' covers from different materials is nowadays wide spread routine by German farmers. Utilization of solid cover for the liquid manure tank (e.g., concrete cover and tent roof) is the most effective and relatively more expensive measure for NH_3 emission reduction. Although application of artificial floating covers is less costly alternative, its NH_3 mitigation efficiency depends on the manure management, the type of stored manure, homogenization intervals, and external factors, i.e., air temperature and solar radiations. Radiation contributes to the heating of the slurry surface, which causes a significant disequilibrium in slurry between NH_3 and TAN in favour of NH_3. However, the introduction of granulate for slurry storage cover prevents the effect of solar radiation and air temperature on the NH_3 losses (Döhler *et al.*, 2002; Sommer, 1997). Beside positive effect of manure storage covering on the reduction of NH_3 emission, the same practise causes increase in N_2O losses and rise of CH_4 emission by nearly 10% (Brink *et al.*, 2005; Amon *et al.*, 2006). Moreover, at the results of conducted experiments Berg *et al.* (2006) found out that N_2O losses are higher from the manure surface covered with granulate and straw (nearly 3 and 5 times, respectively) comparing to uncovered slurry storage. Addition of lactic acid to any type of slurry surface cover, except solid covers, reduces CH_4 emissions by 10-20% (Berg *et al.*, 2004).

Comparing with the broadcasting different manure spreading techniques (e.g., band-spreading trailing hose, band-spreading trailing shoe, and shallow injection) revealed some advantages in NH_3 abatement. Several of these techniques are effective in NH_3 abatement due to an implicit manure land incorporation or/and precise manure application. Slurry extirpators assure precise application of slurry with following mixture of manure with the upper layer of the soil, while slurry injectors introduce manure into middle level of the soil covering. Nevertheless, the employment of these manure spreading techniques is restricted due to their applicability only onto arable land without vegetation, relatively high expenses for the machinery, a low acreage performance and high drug force. From one side, soil disturbance occurring due to injection of untreated slurry results in NH_3 emissions reduction (by about 80%) and a boost of N_2O losses (by up to 100%) (MONTENY *et al.*, 2006; BRINK *et al.*, 2005; PERÄLÄ *et al.*, 2006; METHLING *et al.*, 2002; CHADWICK *et al.*, 2004). From another side, use of injection increase fertilizer replacement values of organic manure, this speaks for reduction of CO_2 and N_2O losses due to less mineral fertilizers applied to the land (WEISKE *et al.*, 2004). According to RODHE *et al.* (2002), employments of shallow injection on grassland may result in yield reduction. Application of slurry with trailing hose and/or trailing shoe avoids soil disturbance and efficiently reduce NH_3 emissions: the first due to manure distribution in narrow bands and the second due to precise manure application underneath the plants and into upper soil surface (METHLING *et al.*, 2002). However, according to MANNHEIM *et al.* (1997), these techniques just significantly slow down NH_3 emission, which boost up during several hours after slurry land application.

In the case of manure land application techniques without implicit incorporation (i.e., broadband and trailing hose), either land cultivation before manure spreading or manure incorporation after land application can be conducted in order to minimize NH_3 losses. Direct incorporation of manure into the soil during, e.g., next 4 hours after land application allows the reduction of NH_3 emission by ca. 90-100% (DÄMMGEN *et al.*, 2009). However, the NH_3 abatement efficiency of manure land incorporation depends on the NH_3 amount emitted before the implementation of this practise. That is why the time span between spreading and incorporation is very important to consider: the longer the delay of incorporation the higher amount of NH_3 emitted and the lower the NH_3 abatement efficiency of the technique. Moreover, relatively high PM emission could be expected from manure incorporation activity. However, there no scientific data on the amount of PM emitted from ploughing the soil, where manure has been applied to. MEISINGER *et al.* (2000) states that the manure incorporation has a positive side effect on the yield, due to an improved N utilization by plants.

The type of land management influences the choice of manure spreading technique and therefore of NH_3 abatement measure. Thus, spreading techniques, which are applicable for arable land without vegetation or with crop residues, are not suitable for the grassland. For instance, by perennial crops and grasslands, manure applied through broadcasting, band-spreading trailing hose, band-spreading trailing shoe and shallow injection, but not through slurry tooth extirpator. Broadcasting of manure onto vegetation, even yield residues, increases plant contamination and causes boosting NH_3 emission (O'SHEA *et al.*, 2009; UNECE, 2007). The washing of the manure after application from leaves and stems into the soil with water may lead to the reduction of NH_3 emissions, although this measure is costly and causes alongside environmental effects (e.g., surface run-off and leaching) (UNECE, 2007).

Abatement efficiency is dependant on manure properties (i.e., dry matter content, pH, etc.), which adjustment may assure the reduction of NH_3 losses. Thus, MEISINGER *et al.* (2000) mentioned a proportional dependency of NH_3 emission potentials on dry matter content of spread manure. Manure dry matter content also determines the speed of NH_3 volatilization, which is initially slower by dry manure (e.g., poultry litter), but extends over several days (MEISINGER *et al.*, 2000). Dry matter content can be reduced in order to obtain higher manure infiltration rate, for instance, through the dilution of manure with water or addition of slurry to irrigation water at the rate of 1:50. Although this abatement practise reduces NH_3 losses by nearly 60%, there is the risk of plants contamination (DÖHLER, 1990; MANNHEIM *et al.*, 1997; MEISINGER *et al.*, 2000; UNECE, 2007; MKHABELA *et al.*, 2009). Moreover, slurry dilution before application onto agricultural land is related to higher manure spreading costs caused by increased amount of slurry-water mixture (METHLING *et al.*, 2002).

Soil characteristics (e.g., cation exchange capacity (CEC), pH, moisture) have a crucial influence on the NH_3 volatilization. The higher pH of soil leads to the higher TAN concentrations and therefore higher NH_3 emission potential. However, higher CEC can restrict pH increase and reduce NH_3 losses. Although soil type and its characteristics have a great influence on the penetration of animal manure, it is rather plausible to match the technique for the manure land application to the soil and surface type than to change above mentioned soil parameters. For instance, for stony soils and sloping land without vegetation it is worth to apply the pressurized injection of slurry (UNECE, 2007).

Timing of manure land application as well as weather conditions are crucial factors for determining NH_3 emissions from manure land application. Thus, NH_3 losses are negligible during morning hours than in the afternoon and overnight, that is to say under cool and humid ambient circumstances. Alternatively, slurry may be spread before light rainfall (ca. 6 mm). Precipitations after manure application onto the soil lead to NH_3 and CH_4 emissions reduction, but also too high amount N_2O released (BRINK *et al.*, 2005; MKHABELA *et al.*, 2009; SHERLOCK *et al.*, 2002; METHLING *et al.*, 2002; DÖHLER, 1990).

In order to reduce NH_3 losses from mineral fertilizers' land application and considering the variations in NH_3 emission intensities by various fertilizer types (section 2.1.2.1), it makes sense to choose fertilizers with lower NH_3 emission potential. An additional irrigation during the first 15 days after, e.g., urea land application assures significant decrease in NH_3 released. The NH_3 reduction rate is proportional to irrigation water amount. However, application of mineral fertilizers under wet conditions or with following irrigation will lead to higher N_2O losses. Moreover, it is important to apply synthetic N-fertilizers and organic manure not at the same time; otherwise N_2O losses increase (KUCEY, 1988; MONTENY *et al.*, 2004; CHADWICK *et al.*, 2004).

2.2 Impact of PM and NH_3 Emissions on Human and Livestock Health

The surrounding environment in the livestock houses has a great impact on stockman's and animal health and depends a lot on the farm management. In this section impacts of NH_3 and PM, originating from livestock barns, on human and animal welfare are discussed all together for three reasons. Firstly, there are plenty of interlinkages between aerial pollutants at the chemical and physical level and not all of them are fully known. Therefore, a separation of their effects is hardly possible (DEFRA, 2002). Secondly, PM and NH_3 can be the same hazardous for livestock and stockman (WATHES, 1998). Thirdly, diseases caused by both pollutants are of a great concern worldwide (HARTUNG *et al.*, 2007).

Talking about impact of NH_3 on human and livestock welfare, it is important to mention that at concentration of 100 ppm gaseous NH_3 causes inflammation of the mucous membrane in the eye and the respiratory tract (WIBERG *et al.*, 2001), and its high concentrations (e.g., 2,500 ppm) may even be fatal for both humans and animals (DEMMERS *et al.*, 2003). Hence, the pollutions thresholds, beyond which health of stockmen and animals is in danger, must be determined to control the emission. Maximum acceptable concentrations (MAC) are already established for NH_3 in animal barn; they generally lay below nationally defined levels, which vary from 10 to 50 ppm depending on animal type, working time and country. For instance, in England a higher limit is applied for short term exposures, i.e., 35 ppm over 15 min of work. In Sweden the limit is stricter, namely 10 ppm for stockmen (AMANN, 2006). Concentrations of NH_3, often exceeding in poultry and pig houses, also vary between animal management systems. For instance, exposure of stockmen in poultry houses is higher for free range (10.8 mg m^{-3}) than cage (4.8 mg m^{-3}) systems (KOERKAMP *et al.*, 1998).

Health impact of PM may have different character, i.e., mechanical, chemical, toxic, infectious, allergic, and immunosuppressive (KEDER, 2007). A growing number of epidemiological studies have observed that even short term increases in PM air pollution is associated with increased human and livestock mortality from respiratory and cardiovascular disease (HARTUNG *et al.*, 2007; PEREZ *et al.*, 2008). According to UN (2006) the continuous exposure to PM leads to average reduction in live expectancy in Europe by 8.6 months.

It has also been revealed that a long term exposure to $PM_{2.5}$ rather than to PM_{10} effects the mortality level due to higher toxicity per unit mass (DEFRA, 2007a; UN, 2006). Although there is still no agreement about the degree of hazard from various fractions of PM, it is known that PM fraction size determines, where the particles sediment in respiratory system and which hazards they cause for human and animal health (KOLLER, 2005; WHO, 2005). Some studies have disclosed that fine PM (less than $PM_{2.5}$), or respirable fraction, is more harmful for humans than coarse particles (between $PM_{2.5}$ and PM_{10}) or inhalable dust (KOERKAMP *et al.*, 1998; KOLLER, 2005). However, there are still few practical evidences for concluding about the influence of coarse PM on human health (PEREZ *et al.*, 2008).

Beside fraction size, dust composition is also responsible for the health hazard. Thus, bacteria spores and viruses can be bounded to the PM suspended in the barn air, and after sedimentation of dust particles in the respiratory tract of animals and humans they may cause infections (METHLING *et al.*, 2002).

Only few countries have established thresholds for PM emissions, below which no adverse effects on human health are to be expected. They are presented in Table 1.

Table 1 24-hour and annual standards for $PM_{10}/_{2.5}$ in different countries, in µg $PM_{10}/_{2.5}$ m^{-3}

Guidelines	$PM_{2.5}$		PM_{10}	
	24-hours	*Annual*	*24-hours*	*Annual*
USA	35	15	150	50
Canada	30	--	--	--
Mexico	65	15	--	--
Australia	25	8	50	--
WHO-Guidelines	25	10	50	--
European Commission	--	12[a)]-17[b)]	25[a)]-35[b)]	20[a)]-28[b)]
Japan	--	--	100	--
China (Hong-Kong)	--	--	180	55

Notes: [a)] 50% of limit value; [b)] 70% of limit value; [c)] WHO – World Health Organization

Sources: EUROPEAN PARLIAMENT (2008) and WHO (2005)

Tolerance limits for PM, showed in Table 1 are primarily based upon human exposure. The World Health Organization (WHO) recommends that in order to avoid significant harmful effects in the population, the $PM_{2.5}$ 24-hour (24-h) average should not exceed 25 µg m^{-3} and that the annual average must not exceed 10 µg m^{-3} (GUSTAFSSON *et al.*, 2007; KOERKAMP *et al.*, 1998; UN, 2006). According to the WHO, regardless the state-individual standards, the health risks for $PM_{2.5}$ and PM_{10} are likely to be similar in cities in developed and developing countries (PEREZ *et al.*, 2008).

Several countries have proposed maximal concentrations of total and respirable dust in animal barns in a framework of national regulations (METHLING *et al.*, 2002). For the former Democratic Republic of Germany the threshold was 6 mg/m^3. Until now, however, there are no PM thresholds values for Germany for concentration in animal barn, beyond which the working and living conditions are not safe (DEMMERS *et al.*, 2003; METHLING *et al.*, 2002).

Very limited information on the interlinkages between aerial pollutants and animal health is available (WHO, 2005; PEREZ *et al.*, 2008; EUROPEAN PARLIAMENT, 2008). Nevertheless, several studies show that chronic exposure of animals to aerial pollutants worsens the severity of respiratory diseases and affects their well-being and performance (e.g., weight gain for fattened pigs). Moreover, research gives the insight into an evolutionary instinct of livestock such as animals' preferences for fresh air. Thus, HARTUNG *et al.* (2007) discussed the ability of pigs to detect NH_3 in the barn air and avoid areas contaminated with irritants; although animals could tolerate suddenly changed NH_3 concentrations (e.g., up to 100 ppm) (SMITH *et al.*, 1996).

Beside PM emissions from animal barns, there are significant amount of PM emitted from other agricultural activities, where mainly humans are exposed to the pollutants. Thus, diesel exhaust PM (part of the emission from arable agriculture) is easily inhalable substance producing chronic health problems, e.g., bronchitis, asthma, cardiovascular disease, and lung cancer (JONES *et al.*, 1998).

3 POLITICAL REGULATIONS

Political restrictions as an essential part of the economic-ecological modelling in this study (section 5.3) assure better representativeness of a model, while providing a wide field for simulations. The inclusion of policy measures into modelling procedure allows drawing plausible conclusions from PM and NH_3 emission analysis. This chapter provides an overview of the European agricultural policy. In addition, main legislative framework addressing climate policy regulations both at the national and international level is briefly discussed.

3.1 Common Agricultural Policy (CAP)

Since 1962, main postulates and orientations of the CAP have changed adjusting to current problems and requirements of the European agricultural market. Thus, in 1970s prices intervention policy reducing EU reliance on imported food was replaced by a taxation and subsidy policy for agricultural imports and exports. These policies put EU food prices among the highest prices in the world. Radical reforms came into force in 1990s and defined the era of guaranteed prices and rural development. These reforms aimed to break the production dependency on financial support, meanwhile developing rural economy (i.e., its structure and competitiveness) satisfying consumer demands and high requirements to environment protection (RICHARD, 2000; EUROPEAN COMMISSION, 2010).

Common Agricultural Policy reforms are considered in this study, since economic-ecological modelling is based on changes of economic issues. The most important political regulations have been integrated into the modelling process in order to build a model as close to the reality as possible. This work is based on the political information for the year 2003 and prognoses year 2015. Chapter 5 provides a detailed explanation of the years' choice. Following sections introduce their main principles of the CAP 2003 and CAP Health Check (HC) Reform 2015 both individually and in comparison to draw conclusions about changes.

3.1.1 Luxembourg Agricultural Reform

All policy restrictions for the reference scenario are taken from the Luxembourg Agricultural Reform 2003 (Council Regulation (EC) No 1782/2003) introduces. The core principles of the Reform are decoupling of direct support schemes, Cross Compliance (CC), and reduction of a financial aid overflow with a particular annual rate.

Decoupling assures separation of production from subventions in order to increase efficiency of financial support throughout improvement of agricultural goods' competitiveness, training a market-oriented farmer and reduction agricultural prices. In addition to decoupling all individual farm subsidies have to be merged together into a single cumulative payment (EUROPÄISCHE KOMMISSION, 2003).

Member states can keep coupling to production but in limits avoiding adjustment of production amounts. There also were some product specific direct payments untouched by the decoupling policy, e.g., annual subsidy of 45 EUR per each hectare of not fallow area under energy crops[10], direct payments for pulses, shell fruits and industrial potato (BMVEL, 2006).

With embracing of decoupling policy livestock subsidies were abolished. Although this put livestock and fodder production in unfavourable financial situation, farmers learn to rely on common market mechanism and own competitiveness and not on the state financial support.

The obligatory fallow land was kept in the framework of decoupling for direct payment. Financial aid for the set-aside under economic crops was only proposed to farms with the share of fallow land between 10% and 33% of a total farm agricultural area (EUROPÄISCHE KOMMISSION, 2003; BMVEL, 2006).

The connection between decoupled payments and fulfilment of standards in environmental protection, alimentary products security, animal and plants health, animal welfare and job safety assure realisation of the Cross-Compliance (CC) principle. According to it, agricultural production has to be organized in a way, which both agricultural sector and environment will profit from (EUROPÄISCHE KOMMISSION, 2003).

Modulation rule completes the CC principle. Modulation is an obligatory shortage of direct payments for large-scale farms in order to release finances for rural development. In the framework of modulation, funding is redistributed from the first pillar of the CAP (market regulation and direct payments) into the second pillar (rural development). Transferred finances may be used by member states to reinforce programs in climate change, biodiversity, renewable energy, water management, and innovations. Money accumulated due to the modulation procedure has to be distributed over member states based on a size of agricultural area, number of employees in agriculture, and relative income level (EUROPÄISCHE KOMMISSION, 2009a; BVEL, 2005, 2006; HÖLSCHER, 2006). In 2003, the modulation rate of 2% was optional and applicable if cumulative support of farmer reached 10,000 EUR. In 2005, this ceil-

[10] Energy crops from agriculture are processed to energy goods as befoul, electricity and heat (EUROPÄISCHE KOMMISSION, 2003)

ing was cut down to 5,000 EUR and until 2006 the modulation rate equated to 3% (GÖMANN *et al.*, 2009).

In addition, market protection policy was adjusted within the CAP 2003; thus, intervention price in cereal production sector was kept, but monthly financial aid in this sector had to be reduced by 50%. Prices in milk sector had to be reduced asymmetrically: the intervention price for butter by 25% during 4 years and for skimmed milk powder by 15% in the 3 years period. Farmers got milk premium as a compensation payment for milk price reduction: the premium amount depended on the milk yield until 2005 (EUROPÄISCHE KOMMISSION, 2003; BVEL, 2006).

Beside pricing mechanism, the CAP 2003 also changed in quoting regulations: for instance, milk contingent supposed to increase by 0.5% from the year 2006 to 2008 (HÖLSCHER, 2006).

3.1.2 Health Check

The discussion at the board of agricultural ministers in Brussels on 20 November 2008 about European agricultural proceedings ended up with final decisions on a Health Check (HC) Program of the CAP. It will come into force in 2015, and it aims to unify all farm premium models. This reform assures several significant alterations of the CAP 2003.

First of all, the need for further financial support of energy crops is eliminated, as an increasing demand for bio-energy on international markets is followed by rising prices and increasing production. Moreover, due to foreseen abolishment of a minimal obligatory rate for the follow land, the production of economic and energy crops have to increase (EUROPÄISCHE KOMMISSION, 2009a; OSTERBURG *et al.*, 2009).

Secondly, instead of optional modulation, obligatory modulation with slightly increase of modulation rate and stable allowance will get into power.

Thirdly, the situation for milk and sugar contingents will change: thus, milk quota as well as subdivision of sugar beet contingent on the European market into A and B quota have to be abolished. According to a new sugar market directive from 2005, which is valid up to 2014/15, the minimal prices for sugar beet must decrease gradually by 39% and the sugar reference prices by 36% (EUROPÄISCHE KOMMISSION, 2009b; BMVEL, 2006).

Regardless substitution of individual direct payments with cumulative payment the EU-members can save some historically reasonable coupled payments with some exceptions, i.e., suckler cows, goat, and sheep premiums (EUROPÄISCHE KOMMISSION, 2009a).

Despite the switch from the CAP 2003 to the HC Program 2015, many principles still stay common for both CAP variants. For instance, in both reforms emphasize the development of decoupling procedure and maintenance of CC principles. However, decoupling procedure of direct payments will be extended and operation of single payment scheme for 2015 will be simplified (GÖMANN *et al.*, 2009). Although the CC regulation has already shown positive results and there is an intention to keep it, justification of CC rules implementation by all EU member states is only oriented on the cumulative effectiveness of certain standards and seems to be complicated. In the framework of the HC reform standards, CC rules stay optional, but not for member states (EUROPÄISCHE KOMMISSION, 2009a).

3.1.3 Regional Programs

Due to a very specific mergence of agricultural and environmental policies, the regional programs are established. Their objective is to support environment at the regional level and hence to contribute to the emission mitigation targets at the national scale. In the framework of the regional agro-environmental and compensation programs regions/federal states got a financial support for these purposes.

As environmental problems are of high concern in Germany, several of its federal states have their own environment and cultural landscapes protection programs, e.g., NAU[11] in Lower Saxony, KULAP[12] in Brandenburg and Bavaria, MEKA[13] in Baden-Württemberg. These regional directives, introduced in the framework of regional agricultural policy and financed as agro-environmental measures from agricultural political budget, are oriented on the achievement of political environmental targets and generally adapted to the particular regional requirements.

3.2 National Environmental Regulations and International Climate Policy

Environmental pollution is subject to national and international laws, conventions and directives. All these levels are equally important considering a varying character of emission and deposition of different pollutants. This section presents an overview of political programs and

[11] NAU – (Germ., Niedersächsische Agrar- Umweltprogramme) Lower Saxony Agro-environmental Program.
[12] KULAP – (Germ., Kulturlandschaftsprogramm) Cultural Landscape Programm.
[13] MEKA – (Germ,. Marktentlastungs- und Kulturlandschaftsausgleich) Market relief and cultural lanscape regulation.

regulations, controlling the activities fields in agriculture, which the PM, NH_3 and GHG emissions stem from.

In Germany, there are several national environmentally oriented management regulations: the German Federal Imission Control Act 2002 (GFICA; Germ., Bundes-Imissionsgesetz – BImSchG), the German Technical Guidelines on Air Quality Control (Technische Anleitung zur Reinhaltung der Luft – TA Luft) and the Nitrate Directive (DÜV, 2007). These regulations introduce rules and restrictions for farming practises, assure the establishment of closer control of on-going environmental protection processes and allow adjusting of existing international directives to German legislation and specific emission situations. Thus, the GFICA is aimed to prevent impacts of damaging environmental conditions such as air contamination and noise on people, animals, soils, water, and the atmosphere. The GFICA regulates installation of different equipment on farms, approval of these equipment, emissions and imissions, safety tests, condition and operation of motor vehicles, monitoring of air pollution and clean air and noise abatement plans, etc. (BMJ, 2010; SCHIER, 2005).

In the framework of GFICA the regulation TA Luft was established. This regulation aims to protect from impacts of damaging environmental conditions occurring due to air pollution. The protection is assured through prescription of good practises and preventive measures against contamination of air with multiple pollutants and odour. TA Luft defines emission thresholds based on state of the art level for various emission sources felling into the category requiring licensing of abatement equipment. TA Luft regulation also specifies emission domains and pollutant types and prescribes minimal distance between pollutant sources and constructed areas and ecosystems. For instance, by 50 livestock units (LU) per livestock intensive farm and total livestock density of 2 LU/ha, the minimal distance of 180 m from the nearest settlement and 150 m from sensitive to nitrogen plants and ecosystems has to be kept (SCHIER, 2005; BMU, 2002; METHLING *et al.*, 2002).

According to the Nitrate Directive (ND), a minimal manure storing capacity (concrete or steel, below-ground or above-ground circular tanks, or earth-banked lagoons) for German farms must be equivalent to a 6-months excretion rate. The ND regiments the maximal amounts of N from animal excreta, which can be applied to arable land and pastures, i.e., 230 and 170 kg N/ha, respectively. Throughout these thresholds, livestock density is also limited with up to 3 LU per hectare of agricultural area (METHLING *et al.*, 2002). The Directive indicates the time spans of manure land application, when the nutrients supply to the soil would fulfil crops requirements. Beside this, the ND also introduces time period and soil conditions (e.g., water logger and frozen soils), when spreading of manure is banned for practical reasons and environmental protection. However, the deadlines for manure spreading can be adjusted to the specifics of regions (BMJ, 2007).

National environmental legislation is necessary but not sufficient. Transboundary character of some pollutants (sections 1.2.1 and 1.2.2) highlights the importance of international agreements about countries' common actions in emission abatement. They eliminate additional factors affecting farmers' competitiveness by means of redistribution of responsibilities, identification of regulatory areas and establishing similar constrains and regulations for farmers in different countries. This is how international environmental regulations push emissions mitigating efforts to the global level (OENEMA *et al.*, 2004).

Since the first World Climate Conference in Geneva, Switzerland, in 1979, organized as a reaction to a series of climate anomalies in the 1970s, a lot more attention has been attracted to climate related aspects and problems. Additionally, many organizations, programs and agreements of climate safeguarding character have gained legislative power. One of their objectives is to improve the knowledge on ongoing climate processes as well as on the state of water, air and soil pollution, to find out the consequences of climate change for environment and society and to elaborate plausible mitigation strategies (SCHÄFER, 2006). The most important conventions, protocols and programs like convention on Long-range Transboundary Air Pollution (LRTAP), Kyoto Protocol, EU directive on integrated pollution prevention and control (IPPC), and United Nations Environment Program (UNEP) aim environmental protection across borders.

3.2.1 Convention on Long-range Transboundary Air Pollution

Understanding of linkage between sulphur emissions and acidification resulted in high concern on ecosystem damage and, furthermore, led to the development of the Geneva Convention on Long-Range Transboundary Air Pollution (LRTAP), the first international legislative instrument aiming to solve aerial pollution problems at the national and international level. The LRTAP has ratified by 34 countries and the European Community (EC) in 1979 and entered into force in 1983. It plays a leading role in abatement of NH_3 and also addresses long-range transport of sulphur dioxide (SO_2), NO_x, VOC, persistent organic pollutants (POP), and heavy metals through a series of Protocols (SCHÄFER, 2006; DEFRA, 2007a; UNECE, 2005). The Convention introduces two main ways to abate NH_3 losses: carrying out of good agricultural practise and introduction of specific NH_3 reduction measures. These abatement options include reduction of urea fertilizers application, employment of emission abating techniques by slurry storage and land application, and incorporation of the solid manure into the soil during 24 hours after its spreading over the arable land (GRIMM *et al.*, 2005).

In 2004, the LRTAP's field was extended for the control and abatement of PM emissions. The work plan covers research for health impacts of fine particulates in collaboration with WHO, through "the development of monitoring programmes for PM and its atmospheric transport across the European region" (UNECE, 2005). This plan intends to evaluate interrelations between different emissions like PM and SO_2, NO_x, VOC, and NH_3. Although modelling outline as well as information from participating countries have been improved, there is still a necessity for further studies on exposure to PM (UNECE *et al.*, 2001). The LRTAP shows environmental organizations and policy makers at a local level the way, how to act providing proper knowledge and orientation for farmers.

3.2.2 Kyoto Protocol

A new stage of climate protective actions was marked by the world climate conference in Kyoto, Japan, in 1997. Within the framework of the Kyoto Protocol, industrial countries agreed for taking common responsibility to reduce GHG emissions (CO_2, CH_4, N_2O, H-FKW, FKW, and SF_6[14]) between 2008 and 2012 by at least 5% comparing to 1990. The EU committed to the general reduction of 8%, although the obligations of EU member states differ from country to country. Germany ratified the Kyoto Protocol on 27 April 2002, and agreed to reduce emissions of the previously mentioned 6 GHGs by 21% (SCHÄFER, 2006). The Protocol assists to the accepted it parties in the achievement of their emission abatement targets, providing them with the insights into an international emissions trading system. The latter establishes the flexible mechanisms allowing each country to make progress in their commitments under specific conditions (DEFRA, 2007a).

3.2.3 Gothenburg Protocol

The fist of December 1999 was marked with the ratification of a multi-componential "Protocol for abating of acidification, eutrophication and ground-level ozone" by 27 EU-member states in Gothenburg. The aim of the protocol is to improve population's health and state of environment throughout the control and reduction of sulphur, NO_x, VOC and NH_3 emissions

[14] H-FKW – halogenated fluorocarbon, FKW – perfluorinated organic compounds, SF_6 – sulphur hexafluoride

caused by anthropogenic activities. Moreover, it has to ensure that atmospheric depositions and concentrations do not exceed in a long and short term (UNECE, 2005).

The Gothenburg Protocol came into force and was approved by the EU, the USA and Canada in 2005 (UNECE, 2005). The Protocol committed to reduce the emission of the sulphur dioxide by 63%, NO_x by 41%, VOC by 40%, the ground-level ozone by 50% and NH_3 by 17% to 2010 comparing to the year 1990. It is proposed that these reductions have to be reached through the application of Best Available Techniques (BAT), e.g., no use of synthetic fertilizers and implementation of specific abatement measures on each stage of farm management (e.g., manure handling, animal husbandry, and manure land application) (MELSE *et al.*, 2009b). Regardless common expectations from emission reduction practises, the Protocol determines reduction targets for each country (party). For instance, Germany has agreed on reduction of NH_3 emission from 746 Gg in 1990 to 550 Gg in 2010, i.e., by 28%. In addition, reduction of NH_3 emission stemming from fertilizers application must constitute 20% and between 20% and 40% for NH_3 emission from animal housing and manure storage (UNECE, 2005; SCHÄFER, 2006). Beside these pollutants, the Gothenburg Protocol considers both secondary and primary PM (DEFRA, 2002).

3.2.4 EU Directive on Integrated Pollution Prevention and Control

The IPPC directive targets to minimize environmental impact of human activities through setting rules for controlling industrial and agricultural activities. Based on control results (for air, water and land pollutions, waste generation and energy utilization, complying with job safety requirements, etc.) these activities get an operating permit. The permit is issued for the operator after proving the fact that Best Available Techniques (BAT) are employed under consideration of local conditions (i.e., geographical, technical, and environmental). All measures leading to the highest emission reduction and applicable under changing economic and technical conditions belong to the BAT category. However, these techniques are not always standard or widely available (EUROPEAN PARLIAMENT, 2001b; MELSE *et al.*, 2009b).

According to the IPPC the abatement techniques assuring reduction of NH_3 losses by at least 20%, should be employed in new-built animal barns, which do not comply with strict emission requirements. Abatement effects of above-mentioned techniques together with NH_3 reduction from slurry storage confinements must result in at least 40% less NH_3 emission (GRIMM *et al.*, 2005).

Even not advanced technologies are giving acceptable results with a good management. Hence, good management practises are important preconditions for a high quality of advanced technologies and techniques functioning. This implies a significant reduction of industrial and agricultural impacts on environment, improvement of material flows management and rising efficiency of energy use (MELSE *et al.*, 2009b).

Cooperation of EU member states results in BAT reference documents (BREFs) describing reference technique and informing about emissions and consumption levels, which follow the application of techniques not complying with legally binding standards. “Reference Document on Best Available Techniques for Intensive Rearing of Poultry and Pigs” is the BREF devoted to good agricultural practises and techniques applied by intensive livestock farms with more than 40,000 poultry places and/or 2,000 fattened pig places, and/or 750 breeding sow places. The key topics of this document are “nutritional management, housing systems, water and energy use, manure storage, manure processing”, and manure land application (MELSE *et al.*, 2009b).

3.2.5 Other Directives

In order to protect their environment, besides UNECE, many countries have ratified the Gothenburg Protocol, United Nations Framework Convention on Climate Change (UNFCCC), the EC National Emission Ceiling Directive (NEC) and the Directive 2008/50/EC of the European Parliament and of the Council and others.

- United Nations Framework Convention on Climate Change (UNFCCC) was ratified by 189 governments and it aims to stabilize GHG “concentrations in the atmosphere at the level that would prevent dangerous anthropogenic interference with the climate system” (DEFRA, 2007a).
- The NEC Directive came in force in November 2001. As the Gothenburg Protocol, it sets the maximal limits for pollutants responsible for acidification, eutrophication and ground-level ozone, i.e., SO_2, NO_x, VOCs and NH_3, state to emit per year 2010 (EUROPEAN PARLIAMENT, 2001a).
- A new proposed Directive of the European Parliament and of the Council on the Reduction of National Emissions of Certain Atmospheric Pollutants and Amending Directive 2003/35/EC has to replace The NEC Directive, while continuing to be based on its principles. This directive binding reduction objectives for 2020 and 2030. The

reduction objectives are calculated in comparison with the basis year 2005. In addition to the NEC Directive two additional pollutants are considered, namely $PM_{2.5}$ and CH_4 (BOURGUIGNON, 2015; EUROPEAN COMISSION, 2013).

- The Directive 2008/50/EC of the European Parliament and of the Council promotes the development of environmental law at the international level through a created framework for controlling and reducing damages caused by transboundary pollutants to human health and environment. The Directive establishes 24-hours and annual thresholds for PM_{10} and $PM_{2.5}$ (section 1.2.3, Table 1). Additionally, this legal document presumes a possibility for extension of time span for pollution minimization (EUROPEAN PARLIAMENT, 2008).
- The aim of the Directive 96/62/EG from the 27th September 1996 is the determination and description of targets for preserving good air quality and for minimization of air pollutants' damaging effects on human and animal health and on the environment.

Many regional, national and international legal notes aimed to conduct and control environmental protection measures and to assure protection of human and animal well-being. However, in this section only the most significant environmental legislative acts have been mentioned.

4 STUDY REGIONS

For emission analyses in this study, specific regions are chosen. They represent various but common characters of German agriculture. In this work, Baden-Württemberg and Lower Saxony with their respective administrative districts and Brandenburg are considered. In Brandenburg arable agriculture is widespread; Lower Saxony is a region of intensive livestock production; and in Baden-Württemberg fodder-producing farms are well represented. Regional diversification of agricultural production is important, especially when one considers that prevailing activities tend to be responsible for the major emissions. All required information to build-up the model for the analysis of emissions and emission abatement options is obtained for the NUTS 1 and NUTS 2[15] levels (chapter 5).

Before calculating and presenting the results for the PM and NH_3 emissions for each studied German federal state and its administrative units, it makes sense to look at the situation of the agricultural sector in Brandenburg, Lower Saxony, and Baden-Württemberg. Thus, the next section will introduce the state of agricultural business in these areas for 2003 (reference year) and describe natural characteristics of these regions influencing land use, e.g., average annual temperature and precipitations.

4.1 Brandenburg

Brandenburg is the federal state with total area of 29.1×10^3 km^2 and 2.54 million of population (MLUV, 2010). Agricultural areas in Brandenburg ($1{,}329\times10^3$ ha) are featured with sandy soils and soil quality below 40 (in the scale from 10 – bad- to 100 - very good) according to ROSCHKE (2004). This in addition to relatively low annual precipitations (of 500-600 mm) presents very complicated conditions for agricultural production.

Cropping or arable farms represent 37% of total farmers in Brandenburg and occupy nearly 39% of the total agricultural area, which 77.5% account for arable land and 22.1% for grassland. The share of land for other purposes is negligible (ca. 0.4%). Table 2 shows the crop production structure of arable land.

[15] NUTS - Nomenclature of territorial units for statistics – NUTS. It is a three-level hierarchical classification, which subdivides each the EU-state into NUTS 1 regions (e.g., German federal states (Germ., “Länder”)), which are in turn subdivided into NUTS 2 regions (German administrative regions (Germ., “Regierungsbezirke”)) (BVEL, 2005).

Table 2 Land use in administrative regions of Brandenburg, Lower Saxony, and Baden-Württemberg in 2003, in 1000 ha

	BB	LS				Total	BW				Total
		BS	*HA*	*LB*	*WE*		*ST*	*KR*	*FR*	*TÜ*	
Agricultural land	1,329	385	494	812	930	2,620	477	205	335	437	1,455
Arable land	1031	335	414	497	570	1,816	317	144	146	231	837
Cereals	500	209	249	237	235	902	191	76.5	60.9	139	467
Oil crops	124	20.9	28.3	21.7	14.3	85.2	28.8	10.2	8.1	21.3	68.4
Tubers	14.1	54.0	43.3	44.9	6.1	148	17.5	5.5	1.8	1.6	26.4
Field fodder	139	8.5	28.6	92.9	146	276	36.1	12.4	18.0	38.6	105
Set-aside area	167	34.1	40.4	50.5	36.8	162	27.4	16.1	15.2	22.2	80.9
Others	87.4	8.7	24.4	49.5	133	243	16.1	22.8	42.1	8.5	89.5
Grassland	293	48.6	78.4	302	354	783	145	57.0	169	196	567

Notes: BB – Brandenburg, LS – Lower Saxony, BS – Braunschweig, HA – Hannover, LB – Lüneburg, WE – Weser-Ems, BW – Baden-Württemberg, ST – Stuttgart, KR – Karlsruhe, FR – Freiburg, TÜ – Tübingen

Source: FORSCHUNGSDATENZENTREN (2007) and DESTATIS (2008)

Cereals production takes the highest share of arable area, namely 48.6%. Under other important crops such as oil plants, forage crops and tubers are 12%, 13.4% and 1.4% of arable land, correspondingly. Share of set-aside is about 15%, which is equivalent to 151×10^3 ha (DESTATIS, 2008; FORSCHUNGSDATENZENTREN, 2007).

The share of arable land under winter rapeseed increased in 2003 by ca. 7% comparing to 1999; in the same time forage crops cultivation reduced by nearly 14.5%. Potato production takes only a minor part of a total arable area, mainly because of their insecure yield. Very few agricultural land is matching by its properties for sugar beet cultivation (FORSCHUNGSDATENZENTREN, 2007).

Among cereals winter wheat and rye prevail in total arable production with 27.1% and 34.2%, respectively. High rye production can be explained by secure yields even under unfavourable climate and soil conditions. Although between 1999 and 2003 agricultural area under rye crops was diminished by 62.3×10^3 ha mainly due to low returns, a further increase of arable land for rye production in Brandenburg due to the extension of the EU and comparatively more favourable rye yields in this federal state is foreseen by LBV-BRANDENBURG (2010; FORSCHUNGSDATENZENTREN, 2007).

Amount of land under cultivation of wheat, which requires better climate and soil conditions than rye, increased between 1999 and 2003 by ca. 30×10^3 ha. Reasons for the expansion of wheat production are higher returns and progress in wheat breeding activity (LBV-BRANDENBURG, 2010). Winter rapeseed appears to be the prevailing culture among oil crops, as it takes over 83% of land under oil plants; the remained area is under sunflower production. The major part of arable land under fodder cultivation is covered by silage maize (up to 70%). Within the reference year 2003 only about 12.3% of fallow land is under renewable primary products (FORSCHUNGSDATENZENTREN, 2007).

In terms of animal production, Brandenburg has fewer cattle per hectare of agricultural used land than other study regions. The livestock density is nearly 0.45 LU[16]/ha (sections 3.3.2 and 3.3.3) (DESTATIS, 2008). In total Brandenburg posses 614×10^3 animals[17] in cattle category and by 769×10^3 of pigs. Laying hens and broilers represent the major part of poultry production ($6{,}514\times10^3$ animals) (FORSCHUNGSDATENZENTREN, 2007).

Between 1992 and 2002 number of cattle in Brandenburg declined by ca. 15%, while animal population density dropped off by more than 19 animals per 100 ha annually. In the same time, the number of pigs declined by nearly 20% and livestock density cut off by almost 50 animals per 100 ha and year. Although pig husbandry is very important production branch, steady market price fluctuations and increasing fodder costs are obstacles on the way of organization of profitable pig production. This and factors like transformation processes after reunification of Eastern and Western Germany and omission of animal premium lead to further decrease in number of animals. The reduction of cattle heads is caused by low revenue from husbandry of some livestock categories, e.g., dairy cows (LBV-BRANDENBURG, 2010).

4.2 Lower Saxony

Lower Saxony is a German federal state with total area of 47.6×10^3 km^2 and ca. 8 million of population (NIEDERSACHSEN, 2008). Natural characteristics vary broadly across the federal state (NMELV, 2006).

The best lands with yield potential of 0.1 tones per hectare of wheat represent one-fifth of the agricultural area and are located in the south of the federal state, in the mountain foreland, which belongs to the best arable areas of Germany. Three-fifth of the area is represented by dry sandy and bog soils, good matching for rye cultivation. The costal region in the north of Lower Saxony with a high level of groundwater is specialized on fodder growing (more than 43% of farms), occupying nearly 35% of agricultural area (NMELV, 2006).

[16] each LU = 500 kg
[17] Census data are performed in animal places (AP)

The climate of Lower Saxony is temperate, with the annual average temperatures of 8-9°C and sufficient precipitations in average of 600-1000 mm per annum (DWD, 2010).

In Lower Saxony about 80% of land area is under agricultural production ($2,620\times10^3$ ha) (NMELV, 2006; DESTATIS, 2008), whereof 69.3% and 29.9% is occupied by arable land and grassland, correspondingly. Table 2 shows land share under the most important crops in the federal state. The segment of cereals production is ca. 50%, where 42% (386×10^3 ha) is under wheat and around 21.4% (193×10^3 ha) under winter barley production. The cultivation of forage crops occupies 13.4% of arable land, whereof ca. 84% (232×10^3 ha) is under silage maize. Tubers growing accounts for 8.2%, oil crops for 4.7% and other cultures for 15.1% of arable land. Fallow areas take about 9% of arable land (162×10^3 ha) (Figure 3).

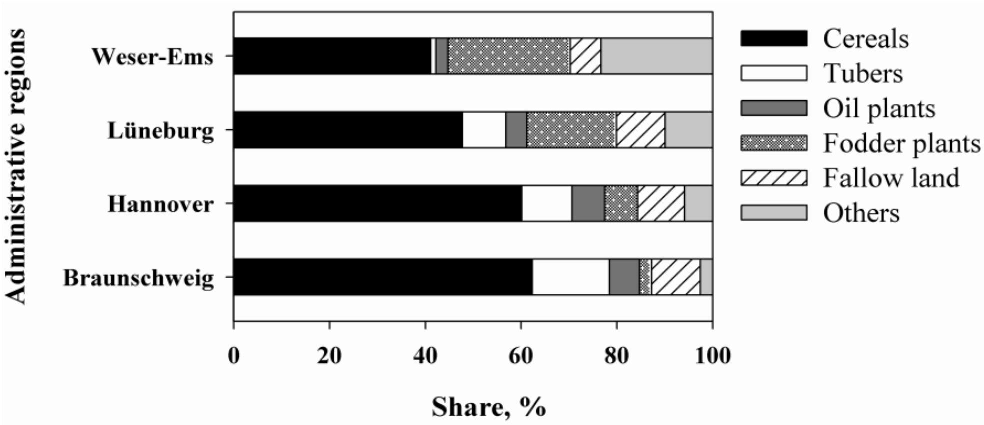


Figure 3 Shares of arable land under different crops (in %) for administrative regions of Lower Saxony in 2003

Source: NMELV (2006)

In terms of livestock production livestock density in Lower Saxony is nearly 1.16 LU/ha. Main animal management activity is pig husbandry, with an emphasis on piglets' production. Pig production is primarily located on the north-west of Lower Saxony (NMELV, 2006). Pigs count for $7,795\times10^3$ animals, cattle for more than $2,661\times10^3$ animals, and poultry for $47,864\times10^3$ birds (FORSCHUNGSDATENZENTREN, 2007). Figure 4 demonstrates the shares of different animal categories in the administrative regions of Lower Saxony.

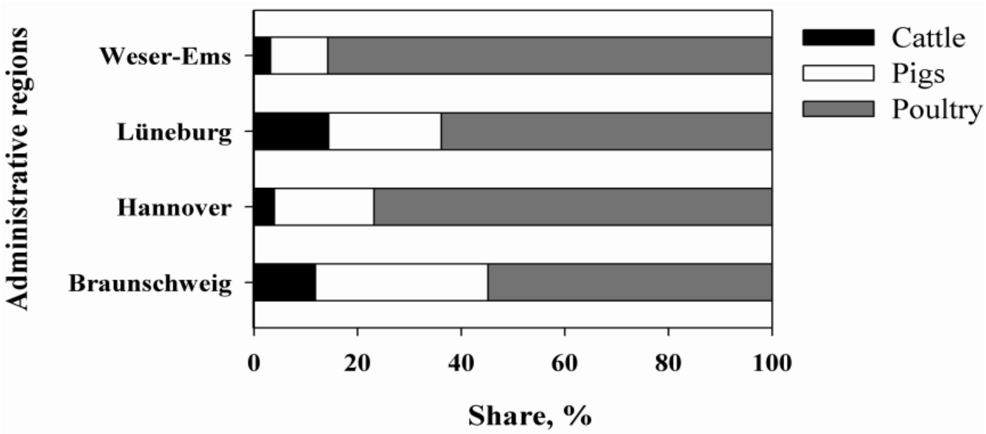


Figure 4 Shares of cattle, pigs, and poultry production (in %) for the administrative regions of Lower Saxony in 2003

Source: FORSCHUNGSDATENZENTREN (2007)

The highest share of pig production is situated in Braunschweig, while Weser-Ems is marked through the prevailing intensive poultry production (Figure 4). The cattle husbandry, however, dominates in Lüneburg.

4.3 Baden-Württemberg

Baden-Württemberg has the total area of 35.8×10^3 km^2 and ca. 10.8 million of population (SLBW, 2010). Natural characteristics vary broadly across the federal state (NMELV, 2006).

The federal state of Baden-Württemberg covers 18 different soil landscapes. Fertile soils of Northern Upper-Rhine low terraces and Alps foreland are basically used for pastures and production of maize and vegetables. Loam soils in the north-west of Baden-Württemberg are good for wine and fruit growing. Since long time favourable climatic conditions and fertile soils in the Necare river basin are intensively used for fruit and vegetables production and viniculture. Arable land and grassland share hilly central part of Baden-Württemberg. Agricultural production, including cereal and grassland production, takes the major part of Allgäu (MUNV, 2010).

The average annual temperatures in Baden-Württemberg vary from 6°C to 10.5°C and the average amount of precipitation differs along the federal state from 600 to 2,200 mm. Air masses from the west stop by Black forest and Swabian Albs and are responsible for a relatively higher precipitations in the western part of Baden-Württemberg (DWD, 2010).

In 2003 average farm size was 22.1 ha in Baden-Württemberg and this value tends to increase over time (SLBW, 2010).

In Baden-Württemberg, two-third (57.6%) of agricultural area is under arable land and one-third (39%) under grassland. The highest share of arable land is under cereal production (467×10^3 ha), whereof winter wheat is leading accounting for 39.6% and winter and spring barley for 21.6% for each crop category (DESTATIS, 2008).

Forage growing on arable land is the next important scope of arable agriculture in Baden-Württemberg, where 48% of farms specialize on forage growing practised on ca. 40% of the total agricultural land ($1{,}455\times10^3$ ha). Forage production occupies 105×10^3 ha, with more than 65% of land under silage maize production. Only about 10% of arable area is fallow land (Figure 5).

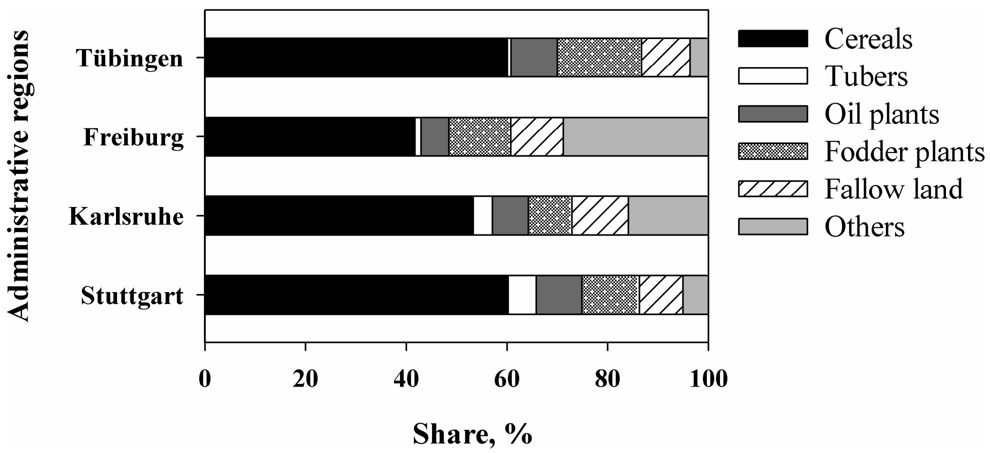


Figure 5 Shares of arable land under different crops (in %) for administrative regions of Baden-Württemberg in 2003

Source: FORSCHUNGSDATENZENTREN (2007)

Structural shifts in agriculture occur due to changes in general agricultural policy framework, increasing farms' specialization and high competitiveness on national, and international agricultural markets. They are reflected in a decreasing number of agricultural farms between 1979 and 2005 (by ca. 50%) and (almost 2.5 times) higher average farm size (up to 23.9 ha). For the same period livestock numbers per farm have risen by 2-6 times depending on animal category (ARNDT, 2006).

Livestock density in Baden-Württemberg is nearly 0.8 LU ha^{-1}. Among all livestock categories poultry count for $2{,}662\times10^3$ animals, pigs for $2{,}302\times10^3$ animals, and cattle for $1{,}138\times10^3$ animals (DESTATIS, 2008). The contribution of individual administrative regions of Baden-

Württemberg to the management of different livestock types, i.e., cattle, pigs and poultry, is presented in Figure 6.

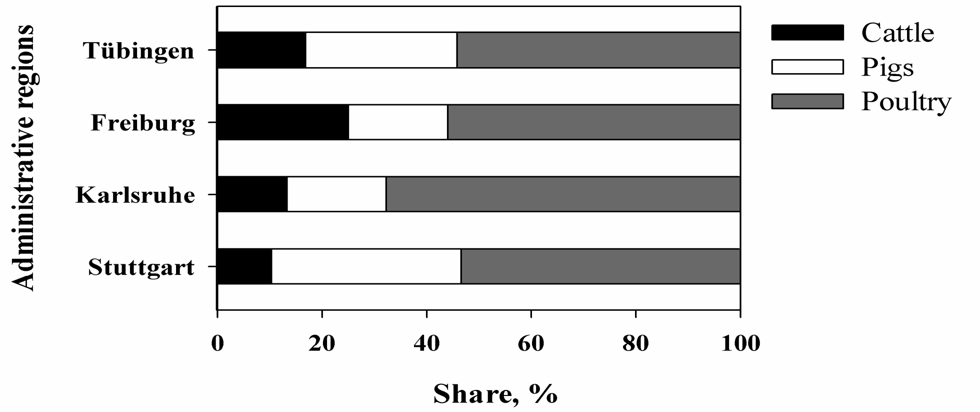


Figure 6 Shares of cattle, pigs, and poultry production (in %) for the administrative regions of Baden-Württemberg in 2003

Source: FORSCHUNGSDATENZENTREN (2007)

From the Figure 6 it can be seen that the uppermost share of pig production in Baden-Württemberg is concentrated in Stuttgart and Tübingen, while the major part of poultry and cattle production is situated in Karlsruhe and Freiburg, respectively.

5 MATERIALS AND METHODS

This chapter discusses the methodology choice throughout the comparison of advantages and disadvantages of different approaches. Beside this, it presents chosen modelling structure, assumptions and approach, including extrapolation procedure, and describes data collection and processing. Also an overview of current estimates of PM and NH_3 emissions from the various agricultural sources, particularly livestock farming and land tillage operations, is an important part of this chapter explaining choice of respective emission factors.

5.1 Choice of the Methodology

A mathematical model is required primarily for analysing current emission situation and its future changes, for adopting emission rates to specific regional conditions (e.g., climate and soil type) and capacities (e.g., size of arable land and livestock numbers). Additionally, with the model the most coherent estimations at regional scale are possible, especially for regions where direct measurements are not feasible from economic or technical perspective.

There are several models measuring environmental pollution, e.g., RAINS[18], RAUMIS[19], GAS-EM[20], and EFEM[21].

A multisectoral model RAINS is based on non-linear approach and evaluating impact of pollutants (i.e., SO_2, NO_x, NH_3, and NMVOC), stemming from a wide range of activities, on human health and ecosystem (IIASA, 2008).

An agricultural sector model, RAUMIS, is also based on a non-linear approach is created for the analysis of relationships between agriculture and environment as well as for making political recommendations for German districts (Landkreise). The model analysis covers only N-based emission, including NH_3 (UNIVERSITY OF BONN, 2006).

An emission model for German agriculture GAS-EM is created to calculate emissions based on statistical data (activities). However, GAS-EM modelling results do not reflect economically optimal farm organization. This policy model not just considers routine emission abatement techniques, but also suggests new mitigation options at the farm level (DÄMMGEN *et al.*, 2009).

[18] Regional Air Pollution Information and Simulation,

[19] RAINS - regionalised information system for agriculture and environment in Germany (Germ., Regionalisiertes Agrar- und UmweltInformations System für Deutschland)

[20] GAS-EM – GASeous Emissions (DÄMMGEN *et al.*, 2009)

[21] Economic Farm Emission Model

The model EFEM is elaborated in the University of Hohenheim, Institute for Farm Management. As an integration of economic and ecosystem models, EFEM provides estimations of disaggregated regional emissions and allows simulation of the effects occurring due to the employment of different emission mitigation options. The model is adjusted to various farm-structures and adapted for finding simultaneous solutions of multidimensional problems. Primary objective of EFEM is economic farm optimization and determination of financial and abatement efficiency of multiple emission abatement alternatives. The model assures a realistic detailed analysis of emissions at both farm and regional scales. Thank to continuously extension of key research issue, EFEM provides the basis for various projects. In this work the analysis of PM and NH_3 emissions from various agricultural systems is carried out (BELETSKAYA *et al.*, 2007; NEUFELDT *et al.*, 2004).

Not all above mentioned model approaches are compatible with the objectives of this study. For instance, RAINS is a very complex model to assure a detailed estimation of the agricultural sector. Controversially, RAUMIS provides a quite detailed analysis of agricultural sector and related environmental problems, but analysing only N-based emissions among all range of pollutants. GAS-EM models and predicts a wide range of emissions, but does not determine an economically optimized choice of agricultural activities causing these emissions and financially preferable abatement measures. Models EFEM and RAUMIS are similar, as their modelling approach is based on the static linear programming. The same as RAINS and GAS-EM EFEM describes process-based relations between agriculture and environment. However, EFEM is not only a model for the analysis of emissions and their abatement but also for the determination of financially feasible emission abatement measures implemented by economically optimal agriculture processes (UNIVERSITY OF BONN, 2006; IIASA, 2008; BELETSKAYA *et al.*, 2007).

5.2 Data Collection and Processing

Comprehensive stages of the economic-ecological modelling procedure are presented in Figure 7. It shows all steps of emission calculation: 1) collection of respective emission information, i.e., relevant bookkeeping and statistical data; 2) selection of typical farms; 3) adjustment of the typical farms' bookkeeping information to the census data through the extrapolation procedure; 4) integration of emission factors and adjusted information on typical farms into the model; 5) model emissions calculations for economically optimal solutions at the farm level; 6) extrapolation of individual farms' results to the regional level. All steps will be discussed in detail in the following section.

Several databases are combined at the first stage of the modelling procedure. Information on activities (e.g., land tilling, harvesting production of various crops, and crop rotation) and capacities (e.g., livestock heads and agricultural areas) is collected from statistical authorities. The sections 2.2.1, 2.2.2 and 2.2.3 present the procedure of data collection from different sources.

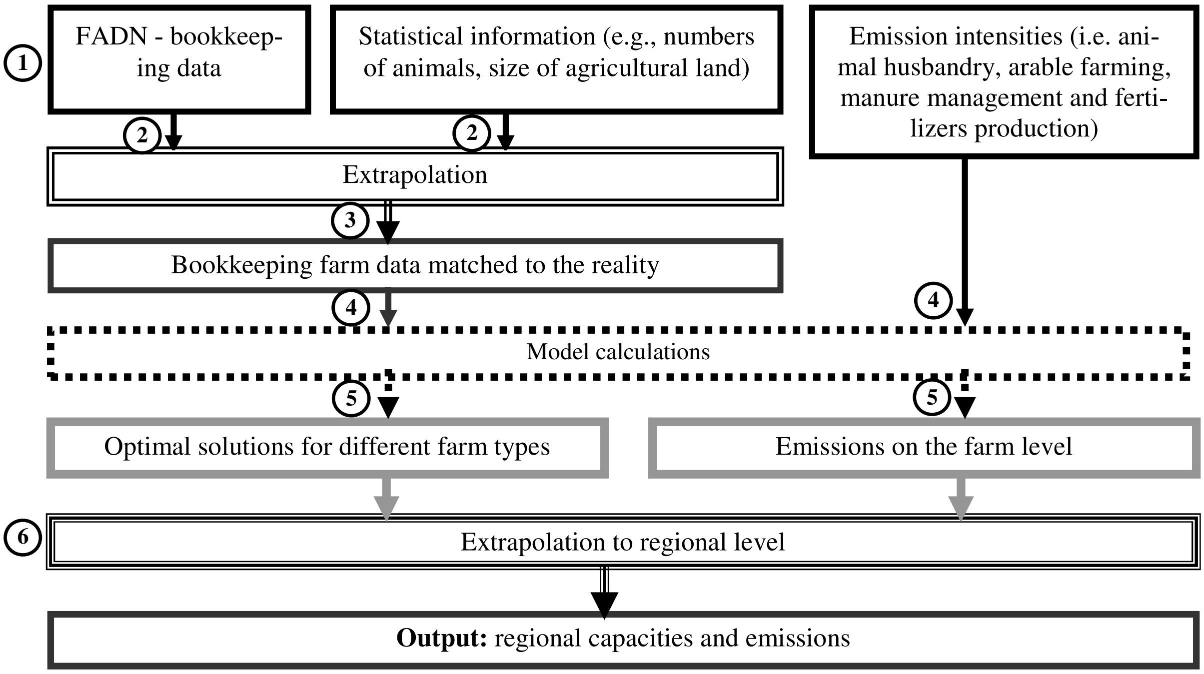


Figure 7 Stages of the modelling procedure

Data (census and bookkeeping data) for the year 2003 are chosen as a reference year for this study, as for this year, comparing to later years, more complete fundamental data for the model elaboration (i.e., results of agricultural survey, data from FADN database) were available to the beginning of the research. Beside this, the exogenous input data like subsidies and policy restrictions are also taken for 2003.

5.2.1 FADN Data

The construction of a region-specific typical farm-model started with collection of bookkeeping data for individual farms in the considered German federal states (Lower Saxony, Baden-Württemberg and Brandenburg). This information is obtained from the Farm Accountancy Data Network (FADN) (FORSCHUNGSDATENZENTREN, 2007). This database contains consistent information on important agricultural products (meat, milk, crops, etc.), costs, prices, areas, and income for all selected regions and administrative districts of various countries. However, FADN does not take into account any changes in intensities of a single production process: input and production intensities are fixed throughout prices, costs and yields for a certain farm-type. This means that the use of FADN data requires an analysis of changes of agricultural management induced by deviations from original farm organization. This divergence has significant influence on fertilizer application, cultivated crops and so forth (VABITSCH, 2006). Bookkeeping FADN data have been categorized and aggregated to match EFEM structure and parameters (Table 3).

Table 3 Original categories in FADN database and their aggregations for EFEM

1	**FADN categories** ***Animals***				
	Cattle		***Pigs***		***Poultry***
A	Male cattle, 12-24 months	**H**	Breeding sows	**J**	Laying hens, elder than 6 months
B	Female cattle, 12-24 months	**I**	Fattened pigs	**K**	Broilers
C	Male cattle above 24 months				
D	Breeding heifers				
E	Fattened heifers				
F	Dairy cows				
G	Other cows (incl. suckler cows)				
2	**FADN categories** ***Arable agriculture and grassland***				
a	Cereal	**f**	Tubers	**k**	Permanent grassland and pastures
b	Other arable cultures	**g**	Other forage plants	**l**	Untended pastures
c	Fallow land	**h**	Temporary grass		
d	Forest land	**i**	Perennial crops		
e	Non-food oil plants	**j**	Orcharding		
3a	**EFEM aggregated categories** ***Animals***				
	Cattle		***Pigs***		***Poultry***
A+C	Fattened bulls	**H**	Sows	**J**	Laying hens
B+D+E	Heifers	**I**	Fattened pigs	**K**	Broilers
F	Dairy cows				
G	Suckler cows				
3b	**EFEM categories** ***Arable agriculture and grassland***				
a+b+c+d-e+f+g+h+i-j			Arable land		
k+l			Permanent grassland		

5.2.2 Census (Statistical) Data

Information for the year 2003 (section 5.2.1), acquired from official regional and national statistical institutions, has been aggregated as shown in Table 4. The statistical data presents regional factor endowments and capacities, but do not provide information on yearly livestock number. This database rather demonstrates the amount of animal places[22] per annum. The later has been recalculated into number of livestock heads by the model implicitly. However, results have been converted back to animal places to compare later with statistical data in the framework of the validation procedure (section 8.2).

5.2.3 Sources of Additional Information

Beyond FADN and census data, further information is obtained from other sources. Thus, price information built into EFEM has mainly been taken from ZMP (2002b, 2004a, 2004, 2004b, 2005a, 2005b) and partially from KTBL (2002) as well as from specifically oriented publications as ZUCKERWIRTSCHAFT (2003) and STATISTISCHES JAHRBUCH (2006). The average prices for the years 2001, 2002, and 2003 have been built into the model. Technical data for Brandenburg and Lower Saxony are presented by TRIEBE (2007). The technical information for Baden-Württemberg is assumed to be the same as in Lower Saxony. The reason for such approximation is a relatively small difference for the average plot size between Baden-Württemberg (2-3 ha) and Lower Saxony (5 ha) (SCHÄFER, 2006; TRIEBE, 2007).

Information on yield of important crops as wheat, rye, rapeseed, maize, barley etc. is taken from KTBL (2000-2003) for the above mentioned three years. A calculated arithmetic average and the processed information have been introduced into the model.

Expert knowledge has been used for many questionable cases and to obtain up-to-date or specific information.

[22] The term "animal place" is used to describe the number of animals counted at a certain date, which is German census practise. The term "place" does not describe the number of places in animal houses potentially used for animal production (DÄMMGEN *et al.*, 2009).

Table 4 Original categories in the census database and their aggregations in EFEM

1	**Census categories *Animals***				
	Cattle		***Pigs***		***Poultry***
A	Calves < than 6 months or weighting < than 220 kg	**M**	Piglets	**W**	Laying hens, above 6 months
B	Young male cattle, from 6 months to 1 year	**N**	Young pigs lighter than 50 kg live weight	**X**	Laying hens, less than 6 months
C	Young female cattle, from 6 months to 1 year	**O**	Fattened pigs, from 50 to 80 kg	**Y**	Broilers
D	Young male cattle, 1 - 2 years	**P**	Fattened pigs, from 80 to 110 kg		
E	Young female cattle, 1 - 2 years, for slaughtering	**Q**	Fattened pigs heavier than 110 kg		
F	Young female cattle, 1 - 2 years, for replacement	**R**	Young sows gestating		
G	Male cattle above 2 years	**S**	Other sows gestating		
H	Female cattle above 2 years, for slaughtering	**T**	Young sows not gestating		
I	Female cattle above 2 years, replacement	**U**	Other sows not gestating		
J	Dairy cows	**V**	boars		
K	Suckler cows				
L	Cows for fattening and slaughtering				
2	**Census categories *Arable agriculture and grassland***				
a	Winter wheat	**k**	Early table potato	**u**	Silage maize
b	Spring wheat	**l**	Intermediate and late table potato	**v**	Other plants
c	Durum	**m**	Potato for food processing	**w**	Fallow land
d	Triticale	**n**	Sugar beet without seed production	**x**	Arable land
e	Rye	**o**	Winter rapeseed for grains production	**y**	Orchards
f	Winter barley	**p**	Spring rapeseed	**z**	Permanent grassland
g	Spring barley	**q**	Sunflower seeds	**aa**	Mow-pasture
h	Oat	**r**	Clover, clover-grass, clover-lucern mixture	**ab**	Permanent pasture
i	Corn to mature	**s**	Lucerne	**ac**	Mountain pastures
j	Early, intermediate, late fodder & non-fodder potato	**t**	Grass growing on arable land	**ad**	Wetland meadows, herding areas
3a	**EFEM aggregated categories *Animals***				
	Cattle		***Pigs***		***Poultry***
A	Calves	**O+P+Q**	Fattened pigs	**W**	Laying hens
E+F	Heifers	**R+S+T+U**	Sows	**Y**	Broilers
D+G	Fattened bulls				
J	Dairy cows				
K	Suckler cow				
3b	**EFEM categories *Arable agriculture and grassland***				
k+l	Potato	**q**	Sunflower seeds	**w**	Fallow land
n	Sugar beet	**r**	Clover-grass	**x**	Arable land
o	Winter rapeseed	**u**	Silage maize	**z**	Permanent grassland

5.2.4 Choice of PM Emission Factors

The choice of PM emission factors proposed some difficulties. Firstly, due to the lack of a worldwide unique inventory system and harmonized sampling procedures an application of emission factors in the modelling procedure is difficult and requires additional pre-processing of emission data. Secondly, there is still not enough information to conclude about the contribution of agricultural activities, e.g., arable farming with relevant operations (like land preparation, crop production and harvesting), to the PM emission. Thirdly, very few studies analyze the uncertainty level of emission factors, and therefore, comparison of information on PM emission from different researches does not give a clear picture of whether emission data are overestimated or underestimated. Fourth problem is related to the drawing of an analogy between European and American (mainly stemming from California) emission information, where sometimes neither difference in climate nor soil conditions is considered. The uppermost reason for this comparison is the lack of relevant European investigation.

Regardless above mentioned difficulties, several studies have been compared in this work, e.g., GRIMM (2007), SEEDORF *et al.* (2004), TAKAI *et al.* (1998), FUNK *et al.* (2007a). Generally, PM emission factors are found as a product of air exchange rates and concentrations, where concentration of primary PM originated from animal barns is determined from dust mass collected on specially assigned filters (SEEDORF, 2004; TAKAI *et al.*, 1998).

Before being implemented into the model, PM emission rates have been evaluated with several criteria. The first criterion is a relevance of emission information for Germany or at least for European countries. Regardless the fact that several national studies, for instance, TAKAI *et al.* (1998), and DEFRA (2002), demonstrate variation of PM emission rates inside of Europe, it is important to limit the choice of PM emission intensities with the framework of the EU. There the natural conditions and agricultural management does not vary drastically. Thus, following selected studies meet the first criterion: KLIMONT *et al.* (2002), UNECE (2006), DÄMMGEN *et al.* (2009), SEEDORF (2004), and TAKAI *et al.* (1998).

At the second stage methodological approaches of these studies have been compared. Thus, UNECE (2006) has the same methodology for air exchange rate calculation as TAKAI *et al.* (1998). However, the suitability of TAKAI *et al.* (1998) methodology for estimation of the emission factors is questionable, as air exchange rate has not been measured, but rather merely calculated with CO_2-balancing method[23]. Both emission rates calculation and measur-

[23] Personal communication of Susanne Wagner, University of Stuttgart, and Friedhelm Schneider (GRIMM company (producer of optical measuring devices), from 21.01.2008

ing techniques used by TAKAI *et al.* (1998) are different from those applied by SEEDORF (2004). Additionally, SEEDORF (2004) suggests to take into account housing periods for various livestock types as the way to reduce the uncertainty of PM emission factors' estimations and also demonstrated, how housing periods can be calculated.

Following the third comparison criterion, studies presenting measured PM fractions have been favoured. Among them are the works of BERRY *et al.* (2005) (for PM_{10}) and HAEUSSERMANN *et al.* (2007) (for $PM_{2.5}$). In major cases, however, emissions of different PM fractions are rather determined based on PM size distribution. Thus, TAKAI *et al.* (1998) measured inhalable, respirable dust and total suspended particles (TSP). Results for $PM_{10}/_{2.5}$ have been derived from these values (UNECE, 2006). SEEDORF (2004) suggests additional recalculation of inhalable/respirable fractions into $PM_{10}/_{2.5}$ using transformation factors, which must to be applied very carefully, because of unclear correlation between above-mentioned dust fractions.

At the fourth stage of PM emission data selection, the information sources differentiating emission factors for various animal types and housing systems has been chosen, as such detailed disaggregation shown in Table 5 matches to the EFEM-approach.

Table 5 $PM_{10}/_{2.5}$ emission factors for livestock production in Germany, in kg $PM_{10}/_{2.5}$ animal^{-1} year*

Animal category	Housing system	PM_{10}	$PM_{2.5}$
Dairy cow	Tie barn	0.70	0.45
	Loose barn	0.36	0.23
Suckler cow	Tie barn	0.70	0.45
	Loose barn	0.36	0.23
Heifer	Solid manure/litter	0.32	0.21
	Liquid manure	0.24	0.16
Fattened bulls	Solid manure/litter	0.32	0.21
	Liquid manure	0.24	0.16
Calves	Solid manure/litter	0.16	0.10
Breeding sow	Solid manure/litter	0.58	0.09
	Liquid manure	0.45	0.07
Fattened pigs	Solid manure/litter	0.50	0.08
	Liquid manure	0.42	0.07
Laying hens	Cages	0.017	0.002
	Aviary	0.084	0.016
Broilers		0.052	0.007

Note: * PM emission caused by fodder mixing and supply constitute 80-90% of total PM emissions from livestock husbandry and are integrated in emission rates for all animal categories (UNECE, 2009a)

Source: DÄMMGEN *et al.* (2009)

DÄMMGEN *et al.* (2009) or National Emission Inventory is the study meeting the major above mentioned criteria. Moreover, in the framework of this study the choice of PM emission intensities already has become a subject for the discussion between specialists, i.e., in atmospheric, technical sciences, etc.

In Table 5, PM emission rates for animal husbandry are presented either for two cattle housing systems, namely tie and loose stall, or for two types of manure handling systems, namely solid and liquid manure. All factors in EFEM have been adjusted for housing periods and number of animals per stable and per animal place. These data are individual for major animals in the model.

A following assumption is made for PM losses from poultry management: a high PM emission from floor system can be regarded as similar to PM released from aviary due to a higher number of birds there. Therefore, PM emission intensity for floor housing system has been incorporated into EFEM as PM emission factor for aviary (Table 5).

Arising from arable farming PM emission can be affected by crop type, soil properties, weather conditions, type of arable operation, type of tilling machinery, and other factors (HOEK *et al.*, 2007). During the modelling of soil tillage operations both preceding cropping and harvesting and following them, e.g., preparation for the next crop production, have been accounted for (HINZ *ET AL.*, 2006). Federal Research Institute for Rural Areas, Forestry and Fisheries (TI[24]) and the Leibniz-Centre for Agricultural Landscape and Land Use Research (ZALF) introduces several studies providing crucial for the modelling procedure and scenario elaboration information on PM emission from arable farming with detailed disaggregation of emission sources by operations, i.e., into ploughing, disking, harrowing, and cultivation.

According to HOEK *et al.* (2007) and FUNK *et al.* (2007a), the approach for calculating PM emission intensities from tillage operations implies taking measurements (of soil moisture and cultivation layer) and assessment of dissipated soil amount. Table 6 demonstrates PM emission factors from different soil preparation operations, which are integrated into the model.

Table 6 $PM_{10}/_{2.5}$ emission factors for tillage operations and diesel burning

	Units	Mean		Min		Max	
		PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Ploughing*	kg ha^{-1}	6.1	0.7	1.2	0.1	11.0	1.3
Cultivating*	kg ha^{-1}	1.86	0.06	--	--	--	--
Diesel burning	kg l^{-1}	0.0063	0.0060	--	--	--	--

Note: * mean value

Sources: PREGGER (2006) and FUNK *et al.* (2005)

[24] TI – Johann Heinrich von Thünen-Institut (former FAL, former vTI - Federal Research Centre for Agriculture)

Minimal and maximal emission values from ploughing, related to dry and moist weather conditions, consequently, and single values for PM emissions from alternative tillage techniques result from the above mentioned approach[25]. Mean values for PM emissions from ploughing have been integrated into EFEM alone with PM emission intensities for reduced-tillage to assure comparability of emission factors between different types of land preparation (Table 6).

The next important source of PM emissions in arable farming after land preparation is harvesting and post-harvesting operations, i.e., unloading, cleaning, and drying. The PM_{10} emission factor for cereal harvesting is a sum of the partial emission rates for harvesting, drying, cleaning, and unloading. Only the highest value for emission rate from harvesting is measured, whilst minimal and mean values are derived from the measured emission factor as 10% and 50%, respectively. The average emission factor is matching to harvesting of dry grains; the lowest emission rate corresponds to PM emissions from harvesting of humid grains; the maximal value reflects PM emission from harvesting of yield under very dry weather conditions. Controversially to emission factors from harvesting, the maximal and minimal PM emission rates from post harvesting activities are measured. The highest PM emission values for unloading, cleaning and drying of grains are resulting from humid grains, while the lowest emission rate arise from dry grains. The reason for this is that at dry conditions major dust is emitted from combine harvesting rather than crop drying. Table 7 presents the cumulative PM emission rates for harvesting and following operations, and for burning of heating oil during yield drying.

Table 7 $PM_{10}/_{2.5}$ emission factors for grain harvesting

	Units	**Mean[1)]**		**Min[2)]**		**Max[3)]**	
		PM_{10}	**PM2.5**	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**
Harvesting[4)]	kg ton^{-1}	0.31	0.069	0.04	0.009	0.82	0.182
Uploading	kg ton^{-1}	0.02	0.004	0.03	0.007	0.04	0.002
Cleaning	kg ton^{-1}	0.03	0.007	0.05	0.011	0.01	0.002
Drying	kg ton^{-1}	0.08	0.018	0.12	0.027	0.01	0.009
Harvesting sum[5)]	kg ton^{-1}	0.44	0.098	0.24	0.053	0.88	0.194
Heating oil use	kg l^{-1}	0.00031	0.00027	--	--	--	**--**

Notes: [1)]**medium** yield moisture is about 19%; [2)]**wet** –the water content in harvested seeds is nearly 25%; [3)]**dry** – the moisture of harvested seeds is about 13-14% [4)] post-harvesting activities are not included (own calculations based on HOEK *et al.* (2007)); [5)] sum of emission rates for harvesting and post-harvesting activities

Sources: HINZ (2004) and HOEK *et al.* (2007)

[25] Personal communication of Susanne Wagner, University of Stuttgart, and Roger Funk, ZALF, from 23.01.2008

So far, measurements and estimations of PM emission factors from harvesting are performed only for PM_{10}. The assessment of $PM_{2.5}$ emission rates is made based on assumptions on particle distribution. Thus, according to UIHLEIN *et al.* (2003), ratio of $PM_{2.5}$ in total suspended particles (TSP) constitutes 10.1%, while 45.4% belongs to PM_{10} (Table 7). It is to be considered that this approach may lead to uncertain results, particularly if PM_{10} and $PM_{2.5}$ are poorly correlated.

Emission intensities from harvesting and post-harvesting are available for cereals, but still missing for other crops. For instance, no measurements of PM emissions are available yet for maize harvesting. However, according to Hinz T.[26], PM emitted from this activity is coarse (section 2.1) and sediment relatively fast. This is the reason for the assumption that maize harvesting does not cause any PM_{10} and $PM_{2.5}$ emissions. It is important to mention that major dust from harvesting stems from plants per se; consequently, PM emission rate depends on the yield rather than on weather conditions. Clover and silage maize are harvested when the seeds' water content is relatively high (more than 19%); hence, it is assumed that no PM is emitted from silage maize and clover harvesting.

Due to the comparison of harvesting moisture conditions for different crops presented in Table 8, it can be seen that average moisture levels for rapeseed and field beans are similar to moisture rates for cereals. Therefore, emission from harvesting of field beans and winter rapeseed is assumed to be the same as for cereals.

Table 8 General information on seeds moisture by harvesting (in %)

Plants	Seeds moisture	Sources
Cereals	14-25	HANUS *et al.* (2008)
Legumes	16-20	HANUS *et al.* (1999)
Rapeseed	15	HEYLAND *et al.* (2006)

To conclude it can be said that PM emission from grains and legumes harvesting is independent from soil type, because in major cases harvester does not disturb the soil. In the case of tuber harvesting, PM is released rather from soil than from crops. However, soil types vary greatly inside of one region; therefore, the application of correct PM emission rate from soils in the modelling approach remains questionable.

In order to obtain PM emissions not only from various farms, but also from other industries contributing to agricultural production, it is necessary to consider PM emission intensities

[26] Personal communication of Susanne Wagner, University of Stuttgart, and Torsten Hinz, TI, from 30.01.2008

from the upstream sector. Particulate matter emissions from upstream sector occur from burning of heating oil, production of electricity and fertilizers, and production and preparation of animal fodder. Respective emission intensities are demonstrated in Table 9.

Table 9 PM emission factors for upstream agricultural production in Germany

PM sources	Units	$PM_{2.5}$	PM_{10}
Heating oil burning	kg l^{-1}	5.3	8.4
Electricity production	kg kWh^{-1}	0.9	1.8
Fertilizer production, incl.			
N-fertilizers	kg $100kg^{-1}$	0.204	0.215
P-fertilizers	kg $100kg^{-1}$	0.0986	0.104
K-fertilizers	kg $100kg^{-1}$	0.0779	0.082
Ca-fertilizers	kg $100kg^{-1}$	0.0112	0.0286

Source: UIHLEIN *et al.* (2003)

Losses of PM occurring due to the livestock fodder production, which farmer buys to fulfil nutritive requirements of livestock, are calculated on the basis of available PM emission rates for arable farming (tillage, harvesting, electricity production and heating oil burning and utilization) and data on crop yields for 2003 and 2015.

5.2.5 Choice of NH_3 Emission Factors

There are more studies presenting measurements for NH_3 losses than for PM emissions. Several works, i.e., AMON *et al.* (2001), DÄMMGEN *et al.* (2009), DEFRA (2002), DEFRA (2007b), KOERKAMP *et al.* (1998), MISSELBROOK *et al.* (2000), NICHOLSON *et al.* (2004), UBA (2008), UNECE (2009a), have been reviewed for measured or assessed data on NH_3 emissions. Variations in NH_3 emissions are found for housing systems, animal types as well as in time and between countries (KOERKAMP *et al.*, 1998).

Countries based difference is the first decisive factor for selection of NH_3 emission rates. Thus, information sources providing estimations of NH_3 emission factors from non-European countries, e.g., USA, have not been considered due to differences in farm management and, furthermore, in climate conditions. Although there is diverse contribution of various European countries to partial[27] and general NH_3 released, emission intensities from European countries are prioritized (KOERKAMP *et al.*, 1998). It is found, that NH_3 emission factor for cattle slurry loose system from the UK is by nearly 30% higher than data for the same animal category and housing system for Germany, but ca. 13% lower for cattle straw based systems

[27] related to individual sources of NH_3 emissions (e.g., animal housing and pasture)

(DEFRA, 2007b). However, German NH_3 emission rates for cattle and pig housing appear to be over 15% higher than Dutch data for identical system. Dutch NH_3 emission factors for laying hens overcome German emission intensities by ca. 80% (UNECE, 2009a).

The second comparison criterion for information sources of NH_3 emission data is the methodological approach for emission calculation. On the one hand, there is emission information resulting from unit approach, when independent measurements are taken from each source and stage of manure management (AMON *et al.*, 2001; KOERKAMP *et al.*, 1998; NICHOLSON *et al.*, 2004). On the other hand, some emission estimates resulting from mass flow approach, where NH_3 losses from livestock farming are seen as a part of the N-flow and the effect of emissions alteration on one stage will depend on preceding and following stages of manure management (DÄMMGEN *et al.*, 2009; DEFRA, 2002, 2007b; UNECE, 2009a). A drawback of the unit approach is the difficulty to assess the effects of emission abating efforts on earlier stages of the N-cycle (DEFRA, 2002). To avoid this shortcoming, emission information from the studies using the mass flow method for calculation of NH_3 emission rates is chosen.

In EFEM emission factors for NH_3 are differentiated for each animal category and housing system. Table 10 shows selected NH_3 emission rates presented as the percentage loss of NH_3-N from TAN[28] in excreted, stored and spread animal manure. In the case of manure storage, TAN is determined as a difference of TAN-value after excretion after deduction of ammonium nitrogen looses during livestock housing. For manure land application stage in manure management, TAN is determined as a TAN-value after deduction of NH_3-N losses during housing and storage.

Emission factors for NH_3 emissions for cattle housing vary for different housing techniques, explicitly for loose and tie systems. Though, tie housing of cattle is considered as less profitable for animal welfare comparing to loose system, it emits three times less NH_3 than loose houses due to a smaller surface covered with manure (UNECE, 2007; DÄMMGEN *et al.*, 2009; DÄMMGEN, 2007). The respective figures are presented in Table 10. As no data on NH_3 emission from cattle housed in the system withleachate are available, it is assumed that NH_3 emission factor for leachate is the same as for slurry (Table 10).

[28] Total ammoniacal nitrogen (TAN = NH_4-N (ammonium nitrogen) + NH_3-N (ammonia nitrogen))

Table 10 Partial emission factors for NH_3-N losses (in % from NH_4-N) from cattle, pig and poultry housing systems, manure storage and land application

Animal category	NH_3 source categories	NH_3-source sub-categories	Emission rates
Cattle	Housing system	Tie system, slurry	7.8
		Loose system, slurry	23.6
		Tie system, solid manure	7.8
		Loose system, solid manure	23.6
		Tie system, leachate	7.8
		Loose system, leachate	23.6
	Storage	Slurry	17.0
		Solid manure	60.0
		Leachate	25.0
	Land application	Arable land, slurry	50.0
		Arable land, solid manure	90.0
		Arable land, leachate	20.0
		Grassland, slurry	60.0
		Grassland, solid manure	90.0
		Grassland, leachate	20.0
	Grazing		7.5
Pigs	Housing system	Slurry based	25.5
	Storage	Slurry	15.0
	Land application	Arable land, slurry	25.0
		Grassland, slurry	30.0
Laying hens	Housing systems	Aviary	10.1
		Cages, dung belt with drying	4.3
	Storage *)	Dry dung	5.8
		Aviary	6.5
	Land application	Arable land	90.0
Broilers	Housing systems	Free range, solid manure	13.8
	Storage *)	Broilers, litter	7.5
	Land application	Arable land	45.0

Source: DÄMMGEN *et al.* (2009); *) own calculation based on DÄMMGEN (2007) and DÄMMGEN *et al.* (2009)

Losses of NH_3 for both breeding sows' and fattened pigs' housing systems are nearly the same (24% and 27% of NH_3-N from TAN, respectively); therefore, an average value is taken for this study (Table 10). As no information on straw based housing systems for pigs is available for Germany, this type of pig management is not considered in the current study (DÄMMGEN *et al.*, 2009).

It is important to consider the difference in properties between pig and cattle liquid manure, which, in turn, explains discrepancy in NH_3 released. Thus, viscosity of pig slurry is lower comparing to cattle liquid manure. Therefore, pig slurry stored in the open slurry tank can easier be moved by the wind, which leads to higher NH_3 losses. Also lower viscosity of pig liquid manure assures its relatively faster infiltration into soil and, at the result, less NH_3 released from manure land application (Table 10) (DE BODE, 1990; SCHÄFER, 2006). The effect of the ambient temperature on NH_3 losses from spreading pig and cattle liquid manure is different. Thus, if 30% of NH_3 can be released from pig liquid manure land application by 20°C, the same NH_3 losses from spread cattle slurry occur already at the ambient temperature of slightly higher than 0°C (DÖHLER, 1990).

Emission rate of NH_3 for hens in cages with manure-belt system and without additional aeration has not been included in this study, as this practise is considered to be rear in Germany (Table 20, section 5.6).

In the conditions of continental climate, where cows spend more time in barns than grazing, emission rate for NH_3 from pasture is lower than emission intensities from cattle housing (Table 10) (DEFRA, 2002).

In order to reduce NH_3 emission at the stage of manure storage, German farmers generally install different covers for manure storage tanks or allow a natural crust formation, when stirring slurry less. The abatement potentials of various cover types for manure storage have been compared with the reference technique, which implies an absence of surface cover for the same type of storage (Table 11).

Table 11 NH_3 emissions abatement potentials (in %) of different slurry storage covers in comparison to open storage tanks

Covering material	NH_3 mitigation, %		General remarks
	Cattle slurry	Pig slurry	
Natural crust	30-80	20-70	Low efficiency in the case of frequent slurry application
Granulate	80-90	80-90	Adjustment of material losses is necessary[1)]
Hexa-Cover [2)]	Not for cattle manure	90-98	Only for pig slurry, without natural crust, long expected useful life
Floating film	80-90	80-90	Low maintenance requirements; does not suit for big containers due to relatively high costs
Tent roof	85-95	85-95	Low maintenance requirements, no access for rain water
Concrete cover/ v.a. concrete cover[3)]	85-95	85-95	Low maintenance requirements, no access for rain water[5)]

Notes: [1)] 10% of annual losses by granulate; [2)] synthetic floating elements; [3)] vehicle-access concrete cover; [5)] diameter of storage tank is up to 15 m (KTBL, 2002)

Sources: KTBL (2005, 2002)

Amount of NH_3 non-released during manure management in animal barn and manure storage can be emitted during manure application onto agricultural land. This requires employment of NH_3 abating techniques for manure spreading, otherwise, much of the abatement benefit gained due to the implementation of emission reduction techniques during manure storage may be lost. Potentials of NH_3 emission abatement for different ways of manure land application are presented in Table 12. Efficiency of methods for NH_3 reduction is demonstrated in comparison to the reference technique, i.e., broadcasting.

Table 12 NH_3 reduction potentials (in %) of various manure land application techniques for different land managements and types of manure, in comparison to the reference technique

Land application techniques	Animal type	Arable land			Grassland		
		Solid manure	Slurry	Leachate	Solid manure	Slurry	Leachate
Broadcast, splash plate	cattle, pigs, poultry	*reference technique*			*reference technique*		
Band-spreading	cattle	*n/a*	10[2]	10[2]	*n/a*	30[2]	10[2]
trailing hose	pigs	*n/a*	30[2]	10[2]	*n/a*	50[2]	10[2]
Band-spreading	cattle	*n/a*	60[1]	--	*n/a*	40[2]	--
trailing shoe	pigs	*n/a*	60[1]	--	*n/a*	60[2]	--
Shallow injection	cattle	*n/a*	*n/a*	--	*n/a*	60[2]	--
open slot	pigs	*n/a*	*n/a*	--	*n/a*	80[2]	--
Slurry tooth extirpa-	cattle	*n/a*	80[1]	--	*n/a*	*n/a*	--
tor**	pigs	*n/a*	80[1]	--	*n/a*	*n/a*	--

Notes: *n/a* – technique is not practised for particular land or manure type; * technique is mainly applicable on grassland; ** technique is only applicable on arable land

Source: [1] UNECE (2009b); [2] DÄMMGEN (2009)

From Table 12 it can be seen that in case of manure spreading the range of measures for NH_3 abatement for liquid manure is wider than for solid excreta. The common spreading techniques for leachate are broadcast and spreading with trailing hose.

Type of the manure, ambient temperature and soil infiltration rate are taken into account for modelling seasonal changes in NH_3 emission from slurry land application. The basic monthly information on temperatures and precipitations is obtained from German Meteorological Service (DWD, 2010) for the years 2004, 2005, and 2007. The year 2006 is not considered, for marginal alteration of its weather parameters from the average for Germany. Calculated average monthly temperatures are associated with certain time spans in a year, when particular farming practises are conducted.

Infiltration rate in range from low to medium and high has been adjusted to particular manure type based on knowledge about viscosity of slurry. Additionally, different slurry absorption rates of soil were considered for manure application onto arable land and grassland. For grassland's vegetation prevents rapid infiltration of leachate into soil, its intensity for pig liquid manure to arable land is determined as high, but to grassland as medium. The absorption rates for leachate are assumed to be the same. The infiltration rate of more viscous cattle slurry is lower than of pig slurry, i.e., medium for both arable land and grassland.

Seasonal changes of weather conditions strongly influence the volatilized amount of NH_3 (MULVANEY *et al.*, 2008). Assumptions on alteration of NH_3 potential losses under consideration of weather conditions and infiltration intensities are taken from HORLACHER *et al.* (1989) and further on calibrated with NH_3 emission rates for manure land application from DÄMMGEN *et al.* (2009). Ammonia emission rates for different farming block time spans resulting from above-mentioned assumptions are shown in Table 13.

Table 13 NH_3 losses (in % from NH_4-N) from the application of cattle, pig and poultry manure to arable land and grassland

	Slurry		**Leachate**	**Fermented slurry**	
	cattle	**pigs**	**cattle**	**cattle**	**pigs**
Arable land					
March	14.7	6.8	5.5	6.8	6.8
April-July	36.7	18.2	14.6	18.2	18.2
August	50.0	25.0	20.0	25.0	25.0
September-October	36.7	18.2	14.6	18.2	18.2
November-February	14.7	6.8	5.5	6.8	6.8
Grassland					
March	17.6	8.8	8.8	8.8	8.8
April-July	44.0	22.0	22.0	22.0	22.0
August	60.0	30.0	30.0	30.0	30.0
September-October	44.0	22.0	22.0	22.0	22.0
November-February	17.6	8.8	8.8	8.8	8.8

Source: HORLACHER *et al.* (1989)

Data on seasonal NH_3 losses from leachate application onto agricultural land are available only for cattle due to the general assumption that pigs are housed in barns with slurry based systems (section 5.6), while leachate occurs as a product in solid manure based systems. There is also no data on seasonal NH_3 emissions for fermented pig slurry; hence, NH_3 losses from its land application are assumed to be equal to NH_3 emission from pig slurry spreading. However, in the case of cattle fermented slurry NH_3 losses are 50% lower than respective emissions from not-fermented cattle slurry.

5.3 Extrapolation

After collecting bookkeeping and census information, FADN data are checked for their representativeness. For this reason bookkeeping information and regional statistics have been compared and significant differences found. In general, FADN figures are lower than the respective data from regional statistics for identical parameters and regions. Beside this, data for some agricultural categories, e.g., broilers and sugar beet, are absent in the FADN database. There are at least three explanations for the mentioned disparities:

- Firstly, differences could possibly be caused by the exclusion of part-time farming out of bookkeeping database. However, as it is shown in Table 14, the share of part-time farming might be significant.

Table 14 Share of farming on a regular/sideline basis (full-/part-time) in Baden-Württemberg, Brandenburg and Lower Saxony, in 2003

	Individual farms, thds.	Share of farms in region, %
Full-time farms	21.9	34
Part-time farms	38.7	60
BW, total	**64.5**	**100**
Full-time farms	1.8	27
Part-time farms	3.4	51
BB, total	**6.7**	**100**
Full-time farms	30.5	54
Part-time farms	22.6	40
LS, total	**56.3**	**100**

Notes: BW – Baden-Württemberg, LS – Lower Saxony, BB – Brandenburg

Source: DESTATIS (2008)

- Secondly, absence of some specific data can be related to data security issues, when information on farm business is open only for limited authorities, e.g., in Baden-Württemberg.
- Thirdly, it is possible that a large share of poultry management is situated at industrial rather than agricultural enterprises. However, the FADN database only contains information on agricultural units, that is, possibly, why animal category like broilers is not presented in FADN data for some administrative units, for instance Braunschweig, Karlsruhe, and Freiburg.

Data lacking by any of all above mentioned reasons have not been estimated, but rather considered to be equal to zero. By the reason of a strong deviation of FADN data from regional statistics extrapolation factors in a FADN database (number of representative farms of a certain type in a certain region) could not be taken for this study as weighting factors. Thus, in order to calculate extrapolation factors matching for EFEM, the extrapolation procedure elaborated according to the approach presented by SCHÄFER (2006) and KAZENWADEL (1999) is conducted.

There are at least three ways to extrapolate farm results to the regional level in at least three ways: 1) modelling of all farms in a region and extrapolation of results; 2) regarding a whole region as a group of farms; 3) an extrapolation of individual farms' capacity to census data. The third option seems to be the most suitable for this study, as in this case requirements for data are lower than in the other cases. Moreover, the third method allows the consideration of different farm types in a study region (KAZENWADEL, 1999).

Extrapolation procedure is based on an optimization approach, which eases depiction of total regional capacities through weighting of typical farms' capacities. The basic principle of this approach is that test-farms are averaged and assessed at the regional level. For each study region 5 typical farms with factor endowments close to average results are selected according to the business administrative classification (Germ., BWA – Betriebswirtschaftliche Ausrichtung): arable, forage growing, mixed farms and two types of intensive livestock farms, namely with the emphasis on the pig and poultry production. Typical farms have been extrapolated to the regional level. Farm capacities and number of representative farms (extrapolation factors) resulting from the extrapolation are shown in Tables 15-17.

Table 15 Typical farms resulting from the extrapolation procedure and extrapolation factors for administrative regions of Lower Saxony, in 2003

Farm types	Arable land	Grass-land	Sugar beet	Male cattle ≥ 1 year	Heifers	Dairy cow	Suckler cow	Fattened pigs	Breeding sows	Laying hens		Broilers	Extrapo-lation factors
										free range	cages/ aviary		
							Braunschweig						
AF	95.6	--	11.0	--	--	--	--	--	--	--	--	--	***2,226***
FGF	31.5	36.8	--	3	13	40	8	--	--	--	--	--	***865***
ILF_ Pigs	94.8	--	32.0	--	--	--	--	156	25	--	--	--	***785***
ILF_ Poultry	24.7	--	4.0	--	--	--	--	15	52	398	1,696	--	***75.5***
MF	16.8	14.9	--	3	5	--	--	--	--	--	--	--	***1,119***
							Hannover						
AF	78.3	--	12.0	--	--	--	--	--	--	--	--	--	***1,720***
FGF	29.0	26.0	--	5	15	34	3	--	--	--	--	--	***2,135***
ILF_ Pigs	69.6	--	--	--	--	--	--	706	139	--	--	--	***693***
ILF_ Poultry	61.4	--	4.0	--	--	--	--	253	--	--	--	16,696	***204***
MF	151	22.0	15.9	16	5	--	5	--	--	181	789	--	***1,041***
							Lüneburg						
AF	91.1	--	15.2	--	--	--	--	--	--	--	--	--	***1,604***
FGF	23.6	39.2	--	23	25	69	--	--	--	--	--	--	***3,833***
ILF_ Pigs	26.9	--	--	--	--	--	--	545	97	--	--	--	***1,092***
ILF_ Poultry	80.2	--	--	--	--	--	--	--	--	--	--	1,903	***1,346***
MF	31.1	38.5	--	7	8		7	--	--	47	198	--	***3,947***
							Weser-Ems						
AF	28.6	--	0.3	--	--	--	--	--	--	--	--	--	***5,087***
FGF	10.8	37.4	--	19	19	43	--	--	--	--	--	--	***8,508***
ILF_ Pigs	38.5	6.1	--	--	3	--	14	126	222	--	--	--	***1,747***
ILF_ Poultry	48.3	--	--	--	--	--	--	459	10	475	2,066	--	***4,533***
MF	53.6	28.4	--	72	13	12	3	--	--	--	--	25,741	***873***

Notes: AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasise on pig and poultry production, respectively, MF – mixed farms

In Lower Saxony, forage growing farms are prevailing (35%) followed by mixed farms (about 30%). Farm capacities are not evenly distributed among administrative regions. Thus, Braunschweig is the region with 41% of arable farms in Lower Saxony. Arable and forage growing farms in Hannover account for a slightly lesser share, namely 31% and 36% of total farms, respectively. Also, intensive livestock farming with emphasis on both pig and poultry production plays a significant role in this region. The highest number of dairy cattle can be found in Lüneburg, while in Weser-Ems intensive pig and poultry production farms prevail, constituting 30% of total farms in this region (Table 15).

Table 16 Typical farms resulting from the extrapolation procedure and extrapolation factors for administrative regions of Baden-Württemberg, in 2003

Farm types	Arable land	Grass-land	Sugar beet	Male cattle ≥ 1 year	Heifers	Dairy cow	Suckler cow	Fattened pigs	Breeding sows	Laying hens		Broilers	Extrapo-lation factors
										free range	cages/ aviary		
						Stuttgart							
AF	55.1	--	5.2	--	--	--	--	--	--	--	--	--	***2,840***
FGF	15.9	34,6	--	8	37	3	16	--	--	--	--	--	***1,920***
ILF_ Pigs	48.7	--	--	--	--	--	--	193	117	--	--	--	***1,495***
ILF_ Poultry	35.1	4.5	--	30	--	--	--	--	--	--	--	9,156	***49.7***
MF	20.1	28.5	--	5	16	4	7	--	--	223	223	--	***2,745***
						Karlsruhe							
AF	53.9	--	3.1	--	--	--	--	--	--	--	--	--	***1,522***
FGF	7.5	36.5	--	5	25	2	11	--	--	--	--	--	***758***
ILF_ Pigs	31.5	--	2.1	--	--	--	--	--	215	--	--	--	***66.1***
ILF_ Poultry	20.7	44.7	--	26	--	--	21	511	--	1,602	1,602	--	***99.2***
MF	56.8	27.1	--	4	10	7	3	--	--	--	--	--	***919***
						Freiburg							
AF	65.3	--	--	--	--	--	--	--	--	--	--	--	***741***
FGF	17.8	59.8	--	8	35	--	9	--	--	--	--	--	***2,229***
ILF_ Pigs	32.9	--	--	--	--	--	--	198	53	--	--	--	***342***
ILF_ Poultry	13.1	--	--	--	--	--	--	--	--	2,380	2,380	--	***107***
MF	52.8	41.4	--	4	--	30	17	10	--	--	--	--	***861***
						Tübingen							
AF	41.1	--	--	--	--	--	--	--	--	--	--	--	***3,009***
FGF	14.5	50.6	--	8	47	3	16	--	--	--	--	--	***3,439***
ILF_ Pigs	13.8	--	--	--	--	--	--	--	128	--	--	--	***723***
ILF_ Poultry	38.3	--	1.1	--	--	--	--	349	--	--	--	576	***679***
MF	17.0	17.6	--	1	13	2	8	--	--	240	240	--	***1,258***

Notes: AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production, respectively, MF – mixed farms

Table 16 shows that about 50% of all farms in Baden-Württemberg are forage growing farms, while about 30% are mixed farms. Freiburg is the most representative region in terms of number of forage growing farms (52%). Stuttgart and Tübingen are two administrative regions with the highest endowments of arable land in Baden-Württemberg (65% of total arable area), where arable farms represent 31% and 33%, correspondingly. Nevertheless, forage growing farms are prevailing farm type in Tübingen (ca. 48%), while mixed farms are the major farm type in Stuttgart (30%). Regardless the lowest share of arable land in Baden-

Württemberg (17%), arable farms in Karlsruhe account for 41% of all regional farm types. Although, the spread of intensive livestock farming in Baden-Württemberg is hardly comparable with the development of the same branch in Lower Saxony, intensive livestock farms are relatively good represented in Stuttgart and Tübingen (pig production), and Freiburg (poultry production). The number of intensive livestock farms for these regions constitute over 85% of this farm type in total Baden-Württemberg (Table 16).

Table 17 Typical farms resulting from the extrapolation procedure and extrapolation factors for Brandenburg, in 2003

Farm types	Arable land	Grass-land	Sugar beet	Male cattle >= 1 year	Dairy cow	Suckler cow	Heifers	Fattened pigs	Breeding sows	Laying hens		Broilers	Extrapo-lation factors
										free range	cages/aviary		
AF	396	-	10.0	-	-	-	-	-	-	-	-	-	***1,127***
FGF	102	270	-	47	32	182	45	-	-	-	-	-	***451***
ILF_ Pigs	137	-	-	-	3	-	-	171	1,097	-	-	-	***62.0***
ILF_ Poultry	48.0	-	-	-	-	-	-	3,124	476	7,855	28,678	45,731	***72.0***
MF	546	180	-	19	74	103	74	-	-	-	-	-	***964***

Notes: AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production, respectively, MF – mixed farms

As it can be seen from Table 17, arable farms represent 41% of total farms in Brandenburg. Forage growing and particularly mixed farms are important for cattle husbandry. Intensive livestock farms are not as widely spread in Brandenburg as in Lower Saxony and Baden-Württemberg. These farm types constitute only ca. 5% of total number of farms in Brandenburg (Table 17).

Due to the extrapolation approach, each regional capacity is weight with the respective gross margin to guarantee that they are not overestimated. The relevance of this weighting procedure is obvious. Thus, in the case of poultry farms several hundred and/or thousands of laying hens and broilers are produced, however, the gross margin per animal is quite low (7-9 EUR animal^{-1} and 1 EUR animal^{-1} for laying hens and broilers, respectively). The choice of gross margin as a weighting factor can be explained by the predominant economic character of EFEM. Indeed, if ecological aspects of analysis are of higher concern, other weighting factors such as size of agricultural area or livestock numbers would be taken into account. After weighting of farm capacities the sums of absolute under- and overestimations have to be minimized through the optimization approach (KAZENWADEL, 1999).

The applied extrapolation procedure guarantees a well assessment of regional factor endowments through the multiplication of the adjusted farms capacities with the weighting coefficient (or, in this case, number of representative farms). Extrapolation additionally assures that farm shares in the selected federal states are well represented. Table 18 shows that a good matching between statistical data and modelling results for both distribution of different farm types in administrative regions and their distribution in the complete federal state could be reached. In this table the modelled distributions are established in brackets and compared to the real situation in Lower Saxony, Baden-Württemberg, and Brandenburg for the year 2003.

Table 18 Distribution of farm types (in %) resulting from modelling (in brackets) and according to census database, for Lower Saxony (a), Baden-Württemberg (b), their administrative regions and Brandenburg (b), in 2003

a)

Farm types \ Regions	BS	HA	LÜ	WE	LS
AF	7 (7)	8 (4)	5 (7)	5 (12)	25 (29)
FGF	2 (2)	4 (5)	15 (9)	22 (20)	43 (35)
ILF	0 (0)	1 (2)	1 (3)	6 (4)	8 (8)
MF	2 (3)	5 (3)	6 (9)	12 (12)	25 (27)
NS	11 (12)	17 (13)	27 (27)	44 (48)	100 (100)

b)

Farm types \ Regions	ST	KR	FR	TÜ	BW	BB
AF	8 (11)	5 (6)	4 (3)	6 (12)	23 (31)	37 (42)
FGF	12 (7)	4 (3)	17 (9)	15 (13)	48 (32)	34 (17)
ILF	1 (6)	0 (1)	0 (2)	1 (5)	2 (14)	2 (5)
MF	10 (11)	3 (4)	6 (3)	8 (5)	27 (23)	27 (36)
BW/BB	31 (35)	12 (13)	27 (17)	30 (35)	100 (100)	100 (100)

Notes: BS – Braunschweig, HA – Hannover, LÜ –Lüneburg, WE – Weser-Ems, ST – Stuttgart, KR – Karlsruhe, FR – Freiburg, TÜ – Tübingen, LS – Lower Saxony, BW – Baden-Württemberg; BB – Brandenburg; AF - arable farms, FGF – forage growing farms, ILF – intensive livestock farms, MF – mixed farms

The fact that factor endowments in FADN data are higher than statistical average can serve as the explanation of some deviations of modelling results from bookkeeping information.

Established typical farms are built into EFEM after implementation of extrapolation approach and comparison of real data and modelling results.

5.4 EFEM Structure and Approach

The objective of economic analysis in EFEM corresponds to farmers interests and is oriented on the maximization of individual farm gross margins. These farms are regarded as representative (typical) for all farms of the same type in the same region, and their objective function can be expressed parametrically as follows:

$$\max_{x_k} \pi_k = (p_i - c_i) \times x_{k,}$$

$$\text{s.t. } A_k \times x_k \leq z_k,\ x_k \geq 0,$$

where π_k is the total gross margin of the k-th farm-type, p_i and c_i are n-vectors for the i-th selling price and variable costs of the i-th production activity, consequently, and x_k is the n-vector of command variables. The constraints faced by farm-type k are defined through A_k and z_k, determining $m \times n$-input-output matrix and m-vector of capacities, respectively (DE CARA S. *et al.*, 2004).

Command variables in EFEM can be both endogenous and exogenous. Thus, area under certain crop (including grassland and set-aside area), quantity of purchased animal feeding and total GHG emissions are endogenous; while, e.g., variables related to policy programs like enrolment in environmental or set-aside programs, subsidies, etc. are examples of exogenous variables.

Under A_k following constraints are defined: cropping area, crop rotation, animal housing places, livestock nutritive requirements, quotas, restrictions imposed by policy and environmental programs (DE CARA S. *et al.*, 2004). In EFEM total land is fixed at an initial land endowment of each farm-type. Crop rotation constraints in EFEM are presented as the maximal shares of arable land under certain crops in a rotation process. The respective restrictions substitute dynamics in crop cultivation in the static modelling framework. These restrictions are introduced on the base of statistical information for the reference year 2003, and further on calibrated to reflect common practises of arable farming in the year 2015, which the projection is made for (section 5.5). Number of livestock heads is restricted by the availability of animal places (DE CARA S. *et al.*, 2004; DE CARA *et al.*, 2005).

EFEM is a mixed integer model, one of special cases of linear programming, where the corresponding variables can be included as both binary and integer. Model's mathematical basis connected to the solving algorithm in MS Excel spreadsheets application assures calculation of optimal farming solutions. The given approach assures precise depiction of farms' technical conditions, allows the choice between production options, make a detailed representation of pollutants' sources possible (ANGENENDT, 2003) and let farmers deal in mutually exclusive policy programs with involvement of different obligations and payments (DE CARA S. *et al.*, 2004). However, beside the advantages, the modelling approach has a draw back, namely its static character (ANGENENDT, 2003). Thus, no factor endowments (inclusive land size, restrictions of crop rotation and livestock numbers) are changing over time. This must be taken into account by interpreting modelling results and making projections.

5.4.1 Farm Structure Module

An economic-ecological model EFEM is not only a combination of economic and ecological factors. Indeed, it has a more complex structure composed of multiple sub-modules. They allow a representation of all relevant production processes of arable farming and grassland management with related mechanization, animal husbandry with a disaggregated feeding module, manure management, and N circulation.

The core of EFEM is a production module, where all sub-modules along with energy, emission, and stock flow parameters for the quantification of emissions stemming from agricultural operations are merged together. Also emissions of NH_3, PM and GHG are differentiated for each production branch they are sourced from. A detailed build-up of the model core is shown in Figure 8.

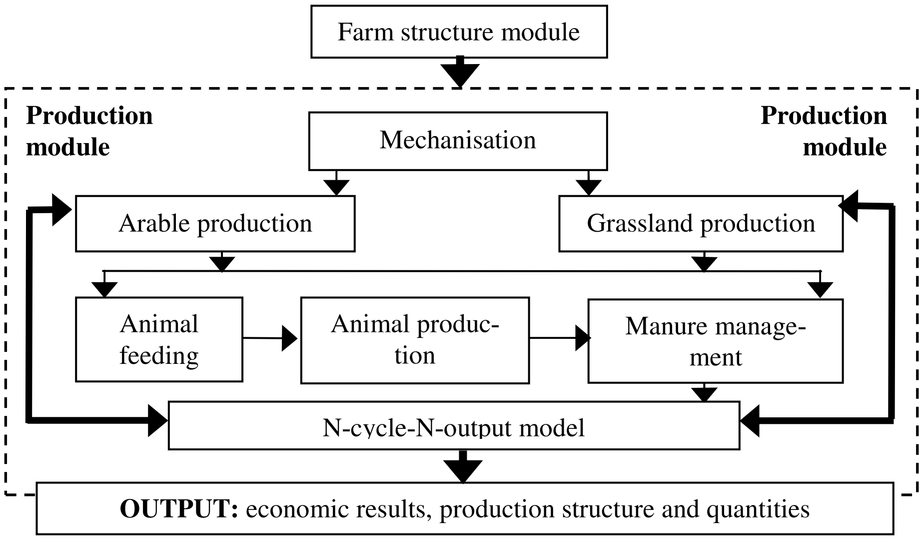


Figure 8 Build-up of the core of EFEM, farm structure module

Source: TRIEBE (2007), modified

All production activities presented in EFEM are disaggregated by the level of input-use and performance. Thus, in general 14 different arable crops are integrated into EFEM, i.e., winter- and spring wheat, winter- and spring-barley, oats, rye, winter rapeseed, sugar beets, potatoes, field beans, sunflowers, grain maize and silage corn, as well as clover-grass. All main crops analysed in EFEM are allocated into three categories: sold or consumed on farm, only for selling and only for on-farm consumption. The main crops for the farm-own consumption include mainly forage crops and grass from pastures for animal fodder. Therefore, the amount of these crop types for farm-own purposes depends on their relative price and nutritional value. Beside main crops, by-products are also analysed in EFEM on farm for feeding purposes, litter, or green manure production and utilisation. Each crop production activity can be combined with different fertilization intensities. In EFEM it is distinguished between two grassland activities: meadow and pasture (DE CARA S. *et al.*, 2004; TRIEBE, 2007).

Livestock production is subdivided according to levels of performance for main animal categories in selected regions. The part of the model devoted to animal husbandry includes data on production of following animal types: dairy and suckler cows, calves, heifers, bulls, fattened pigs, sows, sheep, laying hens, and broilers (TRIEBE, 2007). Animal feeding is determined endogenously in EFEM through establishment of nutritional requirements varying for animal types. These requirements are established in such a way that maximal and minimal values for digestible matter, energy, protein and lysine for each livestock category in the animal production module has to be met (DE CARA *et al.*, 2005).

5.4.2 Policy Module

The farm module is interrelated with the political module. Policy modelling assumes integration of relevant issues of the CAP, national German directives (e.g., Nitrate Directive), environmental laws, and political programs into EFEM. This structure assures building of agricultural production and resulted emissions maximally close to the reality and forecasting of the consequences following political changes. Political issues mainly serve as restrictions for certain agricultural activities (like minimal and maximal share of fallow area), but also introduce beneficial conditions for farmers as, e.g., in case of premiums for growing of renewable primary products. Parameters representing political constraints and supports have endogenous character (section 3.1).

5.4.3 Emission Module

The calculation of emissions requires relevant activity data for respective year and emission intensities. The product of these two components results in a total emission generated by a certain activity. Hence, the emission module is closely bounded with the production module of EFEM (Figure 8). Contribution to the emissions compiles input from: agricultural soils and manure storage (N_2O), enteric fermentation and manure management (CH_4), manure management and mineral fertilizers land application (NH_3), livestock management, land tillage, fuel and heating oil burning (PM), fuel and electricity utilization (CO_2).

Greenhouse gas emissions calculations follow the procedure of the IPCC Guidebook and partially the methodology of the German National Emission Inventory. The GHG emission calculation is done on the base of country-specific data on agricultural activities (like number of livestock units and area assigned for certain crops) and emission intensities. All GHG emissions, namely N_2O and CH_4 losses, are converted into CO_2 equivalent by means of GWP factors, i.e., 298 and 25 for N_2O and CH_4, respectively. More information to the modelling of GHG with EFEM can be found in SCHÄFER (2006) and TRIEBE (2007)

Both PM and NH_3 emissions are modelled explicitly, with emission factors as exogenous parameters. This provides a wide field for model simulations. Analysis of the emission alterations, which imply changing of any of exogenous and thereafter variations in endogenous factors, and relevant predictions for the future can be performed thanks to these simulations.

Computation of NH_3 losses has been done with country-specific activity information and NH_3 loss-fractions. Detailed information on the selection procedure for NH_3 and PM emission factors is provided in sections 5.2.5 and 5.2.4, respectively.

Thus, computations of PM emissions have been performed through the following implicit formula:

$$E_t = EF_t \times x_t,$$

where E_t is PM emission stemmed from an agricultural activity *t*, EF_t is PM emission factor for the activity *t* (section 5.2.4) and x_t is the quantitative expression of the activity *t*.

The methods for calculation of NH_3 and PM losses in EFEM are different. Ammonia emission is computed with the mass flow approach. Thus, NH_3 emission factors (section 5.2.5) are combined in one chain of comprehensive calculations of NH_3 losses from all stages of manure management, i.e., manure storage in animal barn and special confinements and manure land application.

Three different branches are considered in EFEM by calculation of NH_3, PM, and GHG emissions: upstream (buying of farm current assets like pesticides, mineral fertilizers, fuel, heating oil and electricity) and agriculture (including all causing emission activities). EFEM is also adjusted for computation of emissions from downstream (emission sourced from biogas and bio-ethanol production). Although not for all pollutants (i.e., for PM) emission intensities for downstream sector are available. By this reason and due to the initial intention to analyse, at the first place, traditional agriculture oriented on the food and forage production, downstream branch is excluded out of the modelling analysis.

5.5 Prognosis

Generally, inventories are needed within relatively short reference period (mainly a year).Further analysis and investigations are based in the information projected from the certain reference year. Projections of future emission developments intend to support an actual study results and to fill out the data gaps, which could not be eliminated for the reference year. Thus, a "business-as-usual" (BAU) scenario is built to demonstrate how modelling results amend after several years, if neither technology nor land distribution, nor farm capacities, but rather market and political conditions change along with frequency distribution of various farm activities. The year 2015 is chosen for BAU, primarily because the time span of 13 years allows staying in certain political framework determined by the CAP measures (section 3.1). This entails forecast-uncertainty for the year 2020 and further years. The degree of uncertainty increases under consideration of changing technological, market and economic conditions.

Major alterations of the model for 2015 are conducted throughout integration of new political measures and restrictions (section 3.1.2) and prices. The projection of prices for 2015 have been provided by the TI[29], as well as some additional future outlooks for costs, i.e., for fertilizers, plant protection, seeds, etc. (OSTERBURG *et al.*, 2009). Then predicted prices for 2015 have been calibrated with the respective figures from 2003 and then integrated into EFEM.

Projections 2015 are made for main crop yield changes by means of regression analysis of crop yield data. Time series of 23 years for Lower Saxony and Baden-Württemberg and 16 years for Brandenburg have been taken for this analysis.

By making projections it is taken into account that requirements to a minimal share of arable land under fallow practise have to be cancelled already before 2015. The maximal share of production of renewable resources on arable land is another important change performed for BAU comparing to the reference scenario 2003. According to AGENTUR FÜR ERNEUERBARE ENERGIEN (2009), already 17% of arable land were under renewable primary products in 2009. A higher share of arable land used for the production of renewable resources is expected after consideration changing political regulations for supports of renewable resources even. Thus, it has been assumed that farmers are able to produce renewable primary crops on up to 20% of arable land.

5.6 Assumptions

Before starting with model calculations for the reference and business-as-usual (BAU) situations and scenarios, certain general modelling assumption have been made. Relevant information on occurrence of housing systems, manure storage and spreading techniques is partially taken from the agricultural sector model RAUMIS (OSTERBURG *et al.*, 2009).

The occurrence of certain emission generating agricultural activities had to assure modelling results close to the reality. Absence of the relevant information for the years 2003 and 2015 become a reason for several simplifications. Thus, data for 1999 have been taken for building up EFEM reference-scenario 2003. BAU-scenario 2015 is elaborated based on the informa-

[29] TI - Johann Heinrich von Thünen Institute, Federal Research Institute for Rural Areas (former FAL, former vTI)

tion on frequency distribution for the year 2010. Moreover, the assumptions shown in Table 19 have been applied to the FADN and census data serving as a basis for EFEM calculations (sections 5.2.1 and 5.2.2).

Table 19 Shares of various housing activities (in %) as weight average values for Germany, with number of animal places[1)] as a weighting factor

Animal type	Housing system	Manure type	2003	2015
Dairy cows	Tie barn	Solid	13	8
	Tie barn	Liquid	33	17
	Loose barn	Solid	3	5
	Loose barn	Liquid	51	70
Fattened bulls	Tie barn	Solid	2	1
	Tie barn	Liquid	3	0
	Loose barn	Solid	3	4
	Loose barn	Liquid	91	94
Suckler cows	Tie barn	Solid	7	7
	Tie barn	Liquid	2	2
	Loose barn	Solid	86	86
	Loose barn	Liquid	5	5
Heifers	Tie barn	Solid	8	8
	Tie barn	Liquid	17	17
	Loose barn	Solid	25	26
	Loose barn	Liquid	50	49
Fattened pigs		Liquid	100	100
		by 1-phase feeding[2)]	29	13
		by 2-phase-feeding[2)]	62	76
		by 3-phase/ multiphase-feeding[2)]	9	11
Sows		Liquid	100	100

Sources: [1)] MEISINGER *et al.* (2000) and UNECE (2007); [2)] personal communication with Mrs. Stefanie Ferle from Agricultural consultancy service for pig husbandry and breeding (Germ., Beratungsdienst Schweinehaltung und Schweinezucht), 14.12.2009.

Table 19 shows different housing systems for cattle considered during the modelling. Neither the FADN nor the census databases give any information on occurrence of certain housing system for cattle. Therefore, it is assumed that farms with livestock number over 20 animal places cattle is housed in loose barn, otherwise in tie barns. Additionally, a hypothesis has been made that 100% of dairy cows in Germany are situated in livestock houses during the whole year, because the majority of German farmers (ca. 80%) keep their dairy cows in barns (BERG *et al.*, 2003). However, grazing occurrence by suckler cows (57%) allows the statement that suckler cows and heifers spend grazing the most part of the year, except the winter time, when they stay in animal house (OSTERBURG *et al.*, 2009). Moreover, it is supposed that suckler cows and heifers in barns are generally kept on a deep litter. There is only a relatively small share of intensive pig farms with solid-manure based management, i.e., 24% and 7% in 2003 and 17% and 4% in 2010 for breeding sows and fattened pigs, respectively (OSTERBURG *et al.*, 2009). Also after STMELFBAYERN (2003) deep litter pig housing is almost out of practise in Germany, mainly due to costly labour and litter material, which must be renewed regularly. Hence, it is stated that 100% of both pig types are kept in barns with slurry management.

Assumptions for housing of laying hens are presented in Table 20. After competent advice of Prof. Werner Bessei[30], a hypothesis has been made that all cages in German poultry farms in 2015 are equipped with additional aeration installations for manure belts (section 2.2.3).

Table 20 Assumptions on frequency distribution (in %) of farms with different housing systems for laying hens by German federal states and for the years 2003 and 2015

	2003			2015
	BW [1)]	**LS [2)]**	**BB [3)]**	**Germany [4)]**
Cages, manure belt with drying	50	81	78,5	0
Aviary, deep pit /free range	50	19	21,5	100

Notes: BW – Baden-Württemberg, LS – Lower Saxony, BB - Brandenburg

Sources: [1)] SLBW (2008); [2)] NLS (2005); [3)] IT.NRW (2007); [4)] EUROPÄISCHE KOMMISSION (2009b)

Assumptions on the occurrence of different manure application and storage techniques relevant for calculation of NH_3 emissions for both pigs and cattle are taken from OSTERBURG *et al.* (2009) and demonstrated in Table 21. Straw shuffle is excluded from the list of covering materials for slurry storage in EFEM, as this practise is seldom in Germany[31].

Table 21 Shares of various manure storage and land application techniques (in %) as weight average values for Germany, with manure quantity as a weighting factor

Procedures	Techniques	Cattle manure		Pig manure	
		2003	**2015**	**2003**	**2015**
Manure storage					
	Slurry in barn underneath of slatted floor	35	29	31	35
	Storage in outdoor confinements without cover	1	0	27	21
	Outdoor storage, natural floating cover	42	46	13	12
	Outdoor storage, artificial floating cover	7	11	13	16
	Outdoor storage, concrete cover	15	15	16	16
Manure land application					
	Broadcast on surface, splash plate	78	64	68	45
	Band-spreading trailing hose	18	25	27	44
	Band-spreading trailing shoe	1	2	1	2
	Shallow injection open slot	2	5	2	3
	Injection	1	4	2	6

Source: OSTERBURG *et al.* (2009)

[30] Personal communication from 06.10.2009 with Prof. Dr. Werner Bessei, the Institute for Farm Animal Ethology and Poultry Production, University of Hohenheim

[31] Personal communication with Dr. Elisabeth Angenendt und Dipl.-ing. Susanne Wagner, form 25.09.2009

Different manure application techniques in EFEM are defined for various economic crops, seasons (section 5.2.5), types of land management (arable land with and without vegetation and grassland) and manure amount, which is adjusted according to crops' optimal nutrients intake. Total N content in organic manure and N losses during manure management are considered by calculation of eventual N amount available for plants (section 5.2.5). Amount of manure applied meets requirements for maximal amount of N-input to the agricultural area established by the Nitrate Directive (section 3.2). The possibility to extend land for manure spreading on farms with higher than needed amount of N per hectare of agricultural land is introduced into EFEM as a function of manure exchange (Germ., Güllebörse) for Brandenburg and Lower Saxony. This implies that farmers can sell excess of organic manure to other farms, where N limits are not reached yet.

As there is no information on share of land under mulching practises available, it has been assumed that this type of agricultural activity is performed on over 10% of arable land (OSTERBURG *et al.*, 2009).

Due to introduction of crop rotation by study regions, maximal deviation of EFEM crop production structures from census results by 20% is accepted.

Modelling assumptions and simplifications serve as an important basis for economic-ecological model, analysis of its results and their projection.

5.7 Regional Policy Assumptions

Measures of regional environmental programs, i.e., KULAP in Brandenburg, MEKA in Baden-Württemberg, and NAU in Lower Saxony (section 3.2.5) are integrated into EFEM. Table 22 presents subsidies for environmentally friendly and protective agricultural activities.

Table 22 Agricultural activity dependent subsidies introduced by regional environmental programs

Measures \ Programs	Units	KULAP		NAU		MEKA	
		2003 1)	2009 2)	2003 3)	2009 4)	II (2003) 5)	III (2009) 6)
Mulching	EUR ha^{-1}	--	--	72	40	60	60
Environmentally friendly	EUR LU^{-1}	--	--	15	15	--	--
manure land application	EUR ha^{-1}	--	--	max 30	max 30	20 7); 40 8)	30

Notes: 1) valid from 1.07.2005 till 30.06.2006; 2) valid from 1.01.2007 till 31.12.2010; 3) valid from 21.07.2004 till 31.12.2009; 4) valid from 1.01.2009 till 31.12.2015; 5) valid from 1.01.2000; 6) valid from 1.01.2007; 7) by 1 LU ha^{-1}; 8) 1-2 LU ha^{-1} 46 m^3 ha^{-1}, max 2 LU ha^{-1}

Sources: OSTERBURG *et al.* (2009)

Amount of financial aid varies not only between regions, but also in the framework of the same regional programs over time. Thus, the information for 2003 and 2009 is shown in the table above. The measures of regional environmental programs for 2009 are considered for the prognosis.

Financial support for the introduction of mulching technique and environmentally friendly land application of organic manure is provided only in Lower Saxony and Baden-Württemberg, which land endowments and the livestock densities are higher than in Brandenburg (chapter 4). It makes these regions vulnerable to negative effect of improper manure management and crop production. No relevant policy measures exist in Brandenburg.

6 MODELLING RESULTS

This chapter presents main modelling results for farming activities and for stemming from them PM, NH_3, and GHG emissions. The modelling results have been validated through the comparison of the modelled for the reference year (2003) activities (agricultural area, livestock number, etc.) with the reality (census data). Additionally the impact of the European agricultural policy and regional environmental programs relevant for the study regions (chapter 4) on emissions in 2003 and 2015 is examined and discussed in this chapter.

6.1 Reference Scenario

Reference scenario 2003 is calculated in EFEM with the agricultural activities data (section 5.2.1) and assumptions on occurrence of these activities for the year 2003 (section 5.6).

Farms are classified by their economic success, with gross margin as a classification criterion. Economically optimized capacities of each farm type and each study region, like size of agricultural areas and livestock density, reflect the character of agriculture in a region. In Tables 23*a*, *b*, and *c* emission outputs for PM, NH_3, and GHG losses are aggregated as follows:

- "NH_3 total" is the sum of NH_3 losses from manure management, pastures, and mineral fertilizers' application. Emissions of NH_3 from pastures are part of "NH_3 cattle".
- "$PM_{10}/_{2.5}$ arable" consists of emissions from land tillage, yield harvesting, post-harvesting operations, burning of fuel and heating oil, including respective losses for fallow areas.
- "$PM_{10}/_{2.5}$ animals" is the sum of PM emissions from cattle, pigs, and poultry housing.
- Emissions of PM from agriculture and upstream sector are summed up in the category "PM total". The upstream sector includes production of mineral fertilizers, electricity, fuel, and intermediate products for a further use in agriculture. Particulate matter released from the agricultural sector also includes losses from agricultural machinery on grassland.
- Emissions of GHG are calculated as the sum of CH_4 losses from agricultural production and N_2O and CO_2 emissions from agriculture and upstream sector.

Primarily in the modelling procedure the modelling results for all administrative regions of Lower Saxony, Baden-Württemberg, and Brandenburg have been classified by farm types. On the second stage, a weight average for individual farm group has been calculated out of these outputs using the number of representative farms in a respective category as weighting factors (Tables 15, 16, and 17). The modelling outputs for each federal state are shown in Table 23 as a sum of the absolute results for representative farms of each farm type.

Table 23 Average results of the reference scenario for different farm types in Lower Saxony (a), Baden-Württemberg (b), and Brandenburg (c) and total outputs for these federal states

a)

		AF	FGF	ILF_Pigs	ILF_Poultry	MF	LS
Number of farms		10,438	15,743	3,914	5,453	5,051	40,599
Gross margin	EUR ($\times 10^3$)	48.7	92.4	168	112	64.9	3,557,529
	EUR ha^{-1}	726	1,440	3,227	1,970	884	1,372
Agricultural area	ha	67.0	64.2	52.1	56.6	73.4	2,593,681
Arable land	ha	67.0	19.8	49.0	56.6	60.3	1,816,261
Grassland	ha	--	44.4	3.1	--	13.2	777,421
Livestock density	LU* ha^{-1}	--	1.2	2.3	1.1	0.5	0.9
NH_3 animal barn	kg NH_3-N	--	1,177	2,176	1,203	468	35,961,082
NH_3 manure storage	kg NH_3-N	--	330	795	350	197	11,208,994
NH_3 manure appl.**	kg NH_3-N	--	1019	642	859	618	26,355,419
NH_3 grazing	kg NH_3-N	--	37.1	12.6	--	18.0	806,777
NH_3 min. fertiliz.***	kg NH_3-N	351	58.6	159	133	301	7,455,793
NH_3 total	**kg NH_3-N**	**351**	**2,624**	**3,789**	**2,544**	**1,605**	**80,981,281**
PM_{10} animals	kg PM_{10}	--	30.4	244	289	256	4,301,438
$PM_{2.5}$ animals	kg $PM_{2.5}$	--	19.6	41.4	45.1	40.2	920,032
PM_{10} arable	kg PM_{10}	607	175	447	508	547	16,379,101
$PM_{2.5}$ arable	kg $PM_{2.5}$	117	33.1	85.9	97.5	105	3,137,628
PM_{10} total	**kg PM_{10}**	**626**	**232**	**946**	**1,416**	**1,085**	**27,086,586**
$PM_{2.5}$ total	**kg $PM_{2.5}$**	**134**	**74.0**	**195**	**391**	**270**	**6,814,082**
N_2O total	kg CO_2e	129,823	174,969	78,574	72,478	80,326	5,596,701,064
CH_4 total	kg CO_2e	--	408,031	29,757	32,283	40,954	5,334,234,580
CO_2 total	kg CO_2e	52,156	82,483	99,498	112,210	46,684	4,102,586,017
GHG total	**kg CO_2e**	**181,979**	**665,482**	**207,829**	**216,972**	**167,964**	**15,033,521,660**

b)

		AF	FGF	ILF_Pigs	ILF_Poultry	MF	BW
Number of farms		8,115	8,351	2,627	936	5,770	25,798
Gross margin	EUR ($\times 10^3$)	32.2	74.2	101	79.3	48.5	1,500,693
	EUR ha^{-1}	637	1,174	2,777	2,081	836	1,069
Agricultural area	ha	50.6	63.2	36.4	38.1	58.0	1,404,208
Arable land	ha	50.6	15.1	36.4	33.4	30.2	837,362
Grassland	ha	--	48.1	--	4.8	27.8	566,845
Livestock density	LU* ha^{-1}	--	1.0	1.8	1.3	0.6	0.6
NH_3 animal barn	kg NH_3-N	--	859	1,204	442	152	11,620,020
NH_3 manure storage	kg NH_3-N	--	241	372	125	190	4,198,101
NH_3 manure appl.**	kg NH_3-N	--	765	363	402	422	10,149,930
NH_3 grazing	kg NH_3-N	--	32.4	--	1.0	31.6	489,195
NH_3 min. fertiliz.***	kg NH_3-N	314	43.5	90.3	167	153	4,186,061
NH_3 total	**kg NH_3-N**	**314**	**1,943**	**2,029**	**1,140**	**949**	**30,154,107**
PM_{10} animals	kg PM_{10}	--	22.1	108	224	33.3	870,595
$PM_{2.5}$ animals	kg $PM_{2.5}$	--	14.3	17.6	37.0	13.7	278,999
PM_{10} arable	kg PM_{10}	480	144	344	326	282	7,934,424
$PM_{2.5}$ arable	kg $PM_{2.5}$	92.0	26.9	66.2	62.0	53.9	1,514,541
PM_{10} total	**kg PM_{10}**	**507**	**189**	**594**	**829**	**423**	**10,463,964**
$PM_{2.5}$ total	**kg $PM_{2.5}$**	**117**	**61.8**	**118**	**217**	**122**	**2,681,497**
N_2O total	kg CO_2e	130,470	88,120	35,492	11,267	68,913	2,712,437,093
CH_4 total	kg CO_2e	--	206,711	9,711	5,907	65,998	2,339,696,149
CO_2 total	kg CO_2e	63,924	46,101	46,597	16,986	41,533	1,745,801,021
GHG total	**kg CO_2e**	**178,852**	**327,029**	**245,156**	**246,707**	**235,925**	**6,797,934,263**

c)

		AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB
Number of farms		1,127	451	62	72	964	2,677
Gross margin	EUR (×10^3)	206	340	605	940	506	978,742
	EUR ha^{-1}	521	914	4,421	19,574	697	738
Agricultural area	ha	396	372	137	48.0	726	1,325,923
Arable land	ha	396	102	137	48.0	546	1,030,476
Grassland	ha	--	270	--	--	180	295,447
Livestock density	LU* ha^{-1}	--	0.8	3.4	16.4	0.4	0.4
NH_3 animal barn	kg NH_3-N	--	4,280	8,711	14,770	3,398	6,813,313
NH_3 manure storage	kg NH_3-N	--	1,199	3,201	5,065	952	2,022,711
NH_3 manure appl.**	kg NH_3-N	--	3,729	2,474	13,754	2,847	5,572,325
NH_3 grazing	kg NH_3-N	--	260	--	--	309	415,010
NH_3 min. fertiliz.***	kg NH_3-N	1,752	199	136	654	2,218	4,259,271
NH_3 total	**kg NH_3-N**	**1,752**	**9,666**	**14,521**	**34,242**	**9,724**	**18,667,620**
PM_{10} animals	kg PM_{10}	--	116	566	5,062	97.9	546,491
$PM_{2.5}$ animals	kg $PM_{2.5}$	--	74.6	91.8	748	62.9	153,880
PM_{10} arable	kg PM_{10}	3,353	921	1,161	406	4,607	8,738,179
$PM_{2.5}$ arable	kg $PM_{2.5}$	620	179	215	75.0	861	1,628,273
PM_{10} total	**kg PM_{10}**	**3,434**	**1,161**	**3,312**	**17,606**	**4,972**	**10,661,992**
$PM_{2.5}$ total	**kg $PM_{2.5}$**	**695**	**370**	**639**	**5,524**	**1,175**	**2,520,966**
N_2O total	kg CO_2e	625,482	178,598	33,488	98,953	1,043,451	2,231,088,099
CH_4 total	kg CO_2e	--	396,118	9,952	53,178	682,496	1,286,549,930
CO_2 total	kg CO_2e	249,343	87,270	54,910	178,696	468,198	1,170,118,070
GHG total	**kg CO_2e**	**874,825**	**661,986**	**98,350**	**330,826**	**2,194,146**	**4,687,756,099**

Notes: *livestock unit (500 kg of life weight), **manure land application, ***mineral fertilization; AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasis on pig and poultry production, correspondingly, MF – mixed farms

Each hectare of agricultural land assures gross margin of 1,372 EUR in Lower Saxony, 1,069 EUR in Baden-Württemberg, and 779 EUR in Brandenburg. Among five farm types analysed in this study intensive livestock farms with orientation on pig production bring relatively higher financial gain per hectare and per farm in Lower Saxony (3,226 EUR/ha) and Baden-Württemberg (2,777 EUR/ha) by the uppermost livestock density in these regions, i.e., 2.3 and 1.8 LU/ha, correspondingly. However, in Brandenburg, these are livestock intensive poultry producing farms with relatively higher monetary gain per hectare of agricultural land, namely 19,574 EUR/ha (Table 23).

In Tables 23, it is shown that Lower Saxony contributes 81.0×10^6 kg NH_3-N (or 62%) to the total NH_3 released from three study regions (chapter 4). Meanwhile, the parts of Baden-Württemberg and Brandenburg in NH_3 emitted from animal husbandry are considerably less, i.e., 30.2×10^6 kg NH_3-N (or 23%) and 18.7×10^6 kg NH_3-N (or 14%), respectively. The highest share of NH_3 losses stems from manure management: 92% in Lower Saxony, 88% in Baden-Württemberg, and 79% in Brandenburg. Among the sources of NH_3 emissions, animal barns contribute the most to the NH_3 released from livestock husbandry (48%, 44%, and 46% for Lower Saxony, Baden-Württemberg, and Brandenburg, correspondingly). Manure land application is on the second place with 35% for Lower Saxony and 38% for Baden-Württemberg and Brandenburg. Less NH_3 is released from manure storage and animal grazing (16%, 18%, and 17% in Lower Saxony, Baden-Württemberg, and Brandenburg, respectively). In Lower Saxony, Baden-Württemberg, and Brandenburg, 8%, 12%, and 21% of the total NH_3, correspondingly, is emitted due to the mineral fertilizers land application. Absolute contribution of Lower Saxony to the NH_3 losses from mineral fertilization is the uppermost among study regions, i.e., 7.5×10^6 kg NH_3-N, due to higher amount of agricultural area.

For all study regions, the most part of PM_{10} and $PM_{2.5}$ losses originates from arable agriculture, i.e., of over 50-73% in average for both PM fractions, the lowest figure describes the situation in livestock intensive Lower Saxony and the highest in arable Brandenburg. In study regions with higher agricultural land endowments, as Lower Saxony and Baden-Württemberg, arable farms contribute the uppermost share to the total PM emission. With nearly 30% contribution rate livestock intensive poultry farms prevail in Lower Saxony, while arable farms emit over 50% to the total PM emissions in Baden-Württemberg. In Brandenburg, mixed farms contribute the most, namely 45% in average for both PM fractions to the total PM losses (Tables 23*a*, *b, c*).Shares of PM from animal husbandry in the total PM in Lower Saxony are uppermost comparing to the other study regions, i.e., 16% and 14% of PM_{10} and $PM_{2.5}$, respectively. This is consistent with 1.9 kg PM_{10}/LU and 0.4 kg $PM_{2.5}$/LU of total PM by relatively high livestock density in Lower Saxony (Table 23*a*). The contribution of Lower Saxony to GHG emissions is ca. 2-3 times higher than in other study regions, i.e., 15.0×10^9 kg CO_2e. In these losses dominating shares belong to N_2O and CH_4, namely 37% and 35%, correspondingly (Tables 23*a*, *b*, and *c*).

The absolute inputs of single farms to the total emissions have been extrapolated to the level of federal state and the results presented in Tables 24*a*, *b*, and *c*.

Table 24 Contribution of different farm types to emissions in Lower Saxony (a), Baden-Württemberg (b), and Brandenburg (c) in 2003

a)

	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	LS
Number of farms		10,438	15,743	3,914	5,453	5,051	40,599
NH_3 total	kg NH_3-N ($\times10^3$)	3,667	40,677	14,760	13,873	8,004	80,981
PM_{10} total	kg PM_{10}($\times10^3$)	6,530	3,656	3,700	7,722	5,478	27,086
$PM_{2.5}$ total	kg $PM_{2.5}$($\times10^3$)	1,396	1,160	763	2,130	1,365	6,814
N_2O total	kg CO_2e ($\times10^3$)	1,355,132	1,826,376	820,176	756,552	838,464	5,596,701
CH_4 total	kg CO_2e ($\times10^3$)	--	4,259,151	310,616	336,982	427,486	5,334,235
CO_2 total	kg CO_2e ($\times10^3$)	544,423	860,984	1,038,586	1,171,287	487,305	4,102,586
GHG total	kg CO_2e ($\times10^3$)	1,899,556	6,946,511	2,169,378	2,264,821	1,753,255	15,033,522

b)

	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BW
Number of farms		8,115	8,351	2,627	936	5,770	25,798
NH_3 total	kg NH_3-N ($\times 10^3$)	2,544	15,928	5,330	1,064	5,289	30,154
PM_{10} total	kg PM_{10}($\times 10^3$)	4,111	1,579	1,559	776	2,437	10,464
$PM_{2.5}$ total	kg $PM_{2.5}$($\times 10^3$)	949	516	310	203	704	2,681
N_2O total	kg CO_2e ($\times 10^3$)	1,058,723	715,070	288,005	91,432	559,207	2,712,437
CH_4 total	kg CO_2e ($\times 10^3$)	--	1,677,399	78,802	47,937	535,558	2,339,696
CO_2 total	kg CO_2e ($\times 10^3$)	518,728	374,094	378,121	137,835	337,024	1,745,801
GHG total	kg CO_2e ($\times 10^3$)	1,577,451	2,766,563	744,928	277,203	1,431,789	6,797,934

c)

	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB
Number of farms		1,127	451	62	72	964	2,677
NH_3 total	kg NH_3-N ($\times 10^3$)	1,975	4,245	901	2,467	9,080	18,668
PM_{10} total	kg PM_{10}($\times 10^3$)	3,869	524	205	1,268	4,795	10,662
$PM_{2.5}$ total	kg $PM_{2.5}$($\times 10^3$)	783	167	39.6	398	1,133	2,521
N_2O total	kg CO_2e ($\times 10^3$)	704,810	201,249	37,735	111,503	1,175,791	2,231,088
CH_4 total	kg CO_2e ($\times 10^3$)	--	446,357	11,215	59,922	769,056	1,286,550
CO_2 total	kg CO_2e ($\times 10^3$)	280,967	98,338	61,874	201,360	527,579	1,170,118
GHG total	kg CO_2e ($\times 10^3$)	985,778	745,945	110,823	372,784	2,472,425	4,687,756

Notes: AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; LS – Lower Saxony, BW – Baden-Württemberg; BB – Brandenburg

From the tables it follows that these are either forage growing farms in Lower Saxony and Baden-Württemberg (with ca. 51% and 53%, respectively) or mixed farms in Brandenburg (with 49%), which contributes the most to the total NH_3-N emission. By above mentioned forage growing and mixed farms 98% and 77% of NH_3 losses, respectively stem from manure management. Mixed farms in Brandenburg are also main contributors to the total NH_3 released from mineral fertilization (by 2.1×10^6 kg NH_3-N), while in Lower Saxony and Baden-Württemberg arable farms contribute the most to this NH_3 emission category, i.e., 0.9 and 0.8×10^6 kg NH_3-N, correspondingly (Tables 23 and 24).

Table 24*b* demonstrates that arable farms in Baden-Württemberg are main contributors to the total PM in the federal state, i.e., with 39% and 35% for PM_{10} and $PM_{2.5}$, respectively. However, in Lower Saxony the uppermost part in total PM emissions take intensive poultry producing farms, with 29% of PM_{10} and 31% of $PM_{2.5}$, which reasonable share, i.e., 36% and 21% for PM_{10} and $PM_{2.5}$, correspondingly, stems from livestock management. It can be explained by the fact that this farm category counts for ca. 52% of pigs places in the federal state, 98% of which constitute fattened pigs, PM emission intensive animal category (Table 5). The contribution of the mixed farms in Brandenburg to the total PM emission is the highest among other farm types, i.e., 45% for both PM fractions, due to relatively high number of suckler cows and heifers (nearly 78% and 83% of total number of animal places in the federal state, respectively). However, PM released from animal husbandry by mixed farms in Brandenburg constitute only 2% and 6% of total PM_{10} and $PM_{2.5}$, respectively by this farm type (Tables 24*a*, *c*).

The same to NH_3 emissions the major GHG losses in Lower Saxony and Baden-Württemberg stem from forage growing farms, namely ca. 46% and 41%, respectively (Tables 23*a*, *b* and 24*a*, *b*). The uppermost part of GHG is released from respective farms as CH_4, i.e., nearly 61% for each federal state. In Brandenburg about 2.3×10^9 kg CO_2e (or 49%) of GHGs, whereof 51% are N_2O losses from agricultural soils, are emitted from mixed farms (Tables 23*c* and 24*c*).

The correlation between livestock density and NH_3, GHG, and PM emissions is shown by Figures 9, 10, and 11 for three study regions (chapter 4).

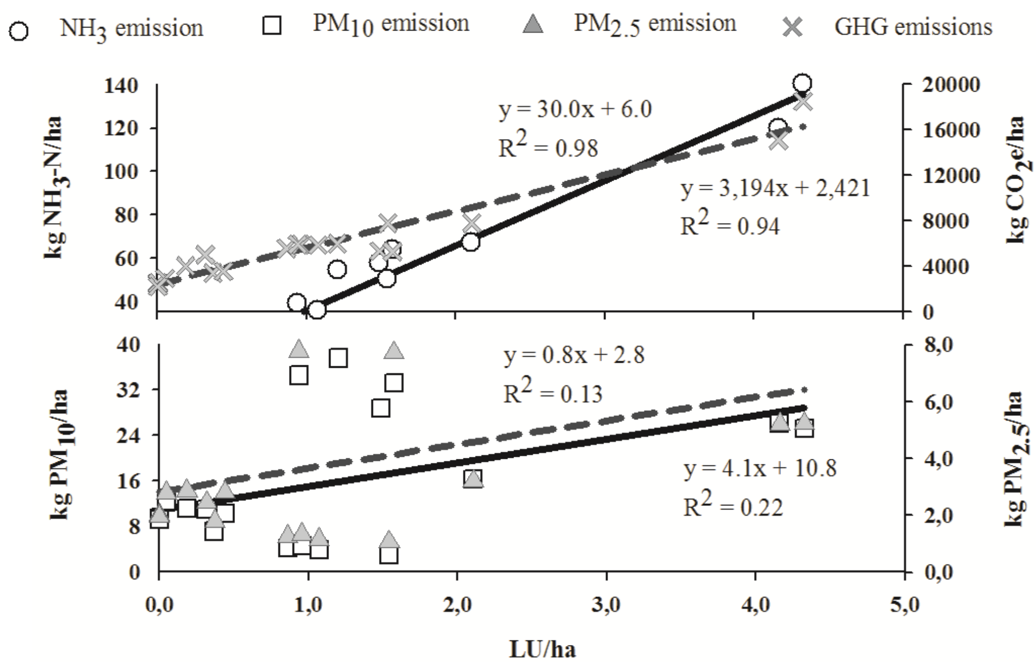


Figure 9 Correlation between livestock density (in LU per hectare of agricultural land) and emissions of NH_3-N, GHG, PM_{10} and $PM_{2.5}$ (in kg per hectare of agricultural area) for Lower Saxony

Note: LU – livestock unit

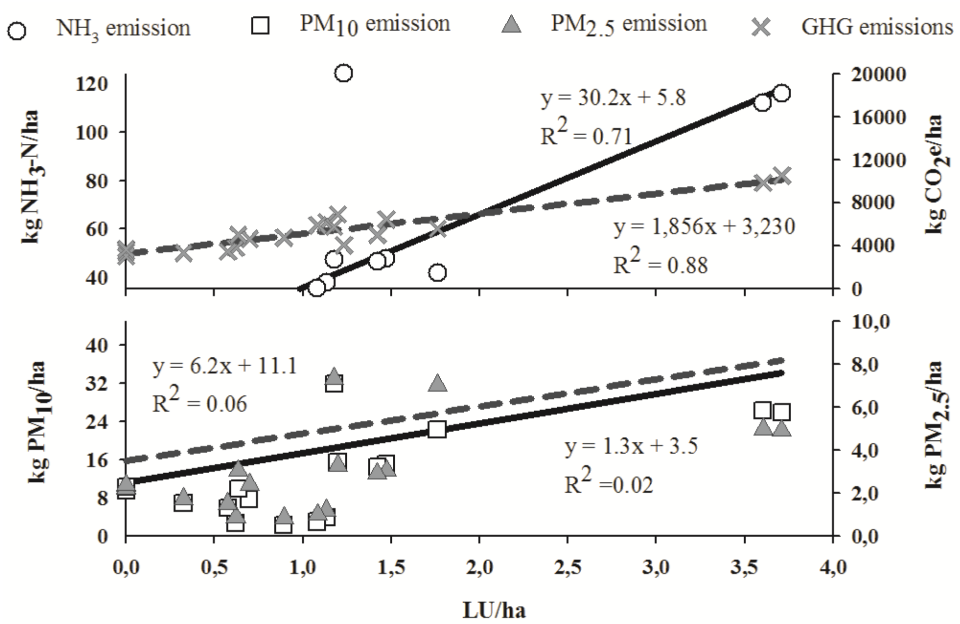


Figure 10 Correlation between livestock density (in LU per hectare of agricultural land) and emissions of NH_3-N, GHG, PM_{10} and $PM_{2.5}$ (in kg per hectare of agricultural area) for Baden-Württemberg

Note: LU – livestock unit

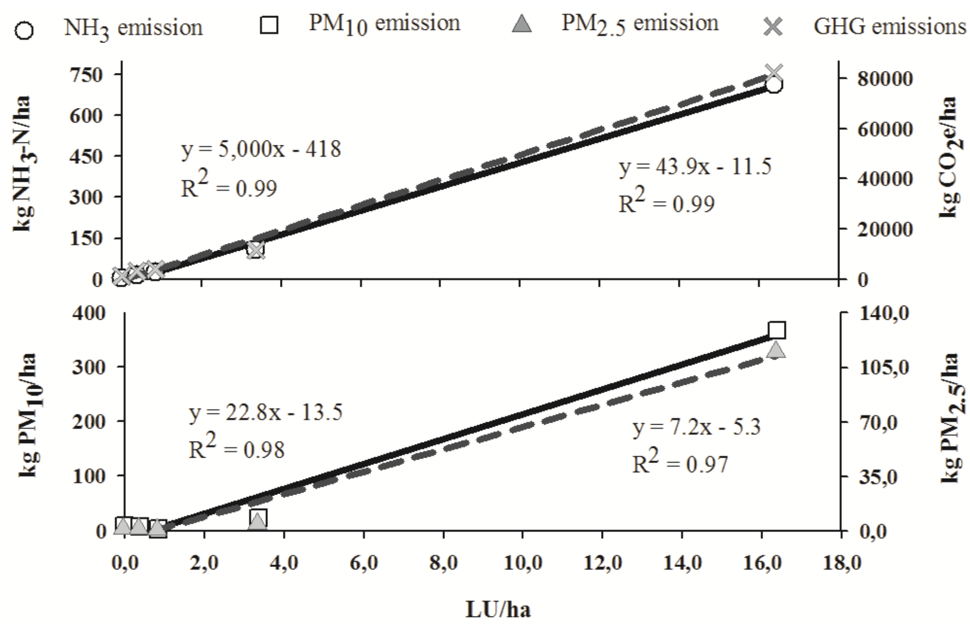


Figure 11 Correlation between livestock density (in LU per hectare of agricultural land) and emissions of NH_3-N, GHG, PM_{10}, and $PM_{2.5}$ (in kg per hectare of agricultural area) for Brandenburg

Note: LU – livestock unit

Figures 9, 10, and 11 demonstrate a trade-off between NH_3 and GHG emissions and livestock density. The correlation between emissions per hectare of agricultural land and LU/ha is explained by the value of the coefficient of determination (R^2): when it is close to 100% then correlation is strong. In the case of NH_3 losses, R^2 explains 99% of variants in Lower Saxony, 71% in Baden-Württemberg, and 98% in Brandenburg. For GHG emissions, R^2 equates to

0.99 for Lower Saxony, 0.88 for Baden-Württemberg, and 0.94 for Brandenburg. However, livestock density is not a determinative factor for PM emissions in Lower Saxony and Baden-Württemberg, for R^2 is 22% and 6%, respectively. Nevertheless, there is a strong correlation between LU/ha and kg $PM_{10/2..5}$ in Brandenburg, i.e., $R^2 = 0.99$; the latter results from fewer observations for regression analysis (Figures 9, 10, and 11). In general, emission results are consistent with the character of agricultural business in study regions. Hence, Baden-Württemberg takes a middle position between Brandenburg with high emissions from arable agriculture and Lower Saxony with prevailing losses from intensive livestock farming.

6.2 Validation of Modelled Capacities

The reference scenario, representing the actual political and production situation in agriculture, has been validated to determine consistency of EFEM with the reality. For this modelling results have been compared, i.e., with metadata, i.e., census information. This chapter describes validation approach and its results. Agricultural land endowments, number of animals and crop production structure from both above-mentioned sources of information are presented in Table 25.

Table 25 Farms average modelling results and comparison of EFEM total outputs with census data for Lower Saxony (a), Baden-Württemberg (b), and Brandenburg (c)

a)

	AF	FGF	ILF_Pigs	ILF_Poultry	MF	LS	
Weighting factor	10,438	15,743	3,914	5,453	5,051	*EFEM*	*Census data*
			ha			**1000 ha**	
Agricultural land	85.5	67.0	58.8	63.2	80.9	2,594	2,620
Arable land	85.5	23.4	57.0	63.2	66.7	1,816	1,816
Grassland	--	43.5	1.8	--	14.2	777	783
				%			
Winter grains	48.0	36.7	48.8	48.8	49.6	45.4	42.9
Summer cereals	11.9	1.1	10.8	10.8	10.9	10.2	8.3
Maize	4.8	--	5.9	5.9	1.0	4.9	4.0
Tubers	12.1	4.1	14.0	14.0	7.4	8.2	8.2
Silage maize	1.9	38.8	2.9	2.9	5.4	9.1	12.8
Clover-grass	--	9.3	--	--	0.6	1.7	0.1
Oil plants	7.6	--	5.3	5.3	10.1	6.2	4.7
Others	--	--	--	--	--	--	18.9
Fallow	12.9	6.0	11.4	11.4	13.8	12.0	8.9
			animal places			**1000 animal places**	
Dairy cow	--	42	--	--	3	702	748
Suckler cow	--	2	4	--	6	72	74
Fattened bulls	--	12	--	--	25	364	365
Heifers	--	22	--	--	3	381	361
Breeding sows	--	--	135	16	--	659	659
Fattened pigs	--	--	466	183	--	3,560	3,560
Laying hens	--	--	--	1,151	390	13,660	13,669
Broilers	--	--	--	5,169	6,435	28,415	28,628

b)

	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BW	
Weighting factor	8,115	8,351	2,627	936	5,770	*EFEM*	*Census data*
			ha			1000 ha	
Agricultural land	53.8	59.3	29.8	38.1	65.4	1,404	1,455
Arable land	53.8	13.9	29.8	26.8	36.7	837	837
Grassland	--	45.4	--	11.3	28.6	567	567
				%			
Winter grains	39.9	29.4	40.1	40.1	37.4	37.9	36.8
Spring grains	20.7	19.8	20.3	20.3	19.8	20.4	18.9
Maize	8.8	8.4	7.4	7.4	10.9	8.9	8.1
Tubers	5.6	1.6	0.1	0.1	--	3.1	3.2
Silage maize	1.0	35.5	1.8	1.8	8.6	8.0	8.2
Clover-grass	--	2.1	--	--	1.2	0.6	2.7
Oil plants	10.2	--	12.6	12.6	6.5	8.2	8.2
Others	--	--	--	--	--	--	13.6
Fallow area	13.5	3.1	13.9	13.9	14.5	12.2	9.7
			animal places			1000 animal places	
Dairy cow	--	31	--	--	9	340	398
Suckler cow	--	2	--	--	11	63	63
Fattened bulls	--	7	--	14	4	91	91
Heifers	--	17	--	4	6	191	163
Breeding sows	--	--	128	--	--	300	300
Fattened pigs	--	--	99	217	3	653	652
Laying hens	--	--	--	1,991	232	2,657	2,662
Broilers	--	--	--	2,410	--	848	874

c)

	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB	
Weighting factor	1,127	451	62	72	964	*EFEM*	*Census data*
			ha			1000 ha	
Agricultural land	342	268	235	253	324	1,326	1,329
Arable land	342	93.7	228	253	267	1,031	1,031
Grassland	--	174	7.0	--	56.9	295	293
				%			
Winter grains	46.7	37.5	46.7	46.7	46.7	46.3	44.2
Spring grains	5.8	0.9	5.8	5.8	5.8	5.6	4.4
Maize	3.1	--	3.1	3.1	--	1.4	1.3
Tubers	2.5	1.5	2.2	2.2	0.4	1.4	1.4
Silage maize	3.3	23.8	3.3	3.3	6.8	6.0	9.5
Clover-grass	--	10.0	--	--	1.4	1.2	0.4
Oil plants	16.6	13.4	16.6	16.6	16.6	16.5	12.9
Others	--	--	--	--	--	--	10.6
Fallow	18.8	8.9	18.9	18.9	19.5	18.8	16.2
			animal places			1000 animal places	
Dairy cow	--	35	--	--	25	155	181
Suckler cow	--	11	--	--	19	92	92
Fattened bulls	--	12	--	--	5	40	40
Heifers	--	20	--	--	15	92	86
Breeding sows	--	--	274	119	--	102	102
Fattened pigs	--	--	43	787	--	236	236
Laying hens	--	--	--	9,133	--	2,632	2,632
Broilers	--	--	--	11,433	--	3,295	3,295

Notes: AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; BW – Baden-Württemberg, LS – Lower Saxony, BB – Brandenburg

As it has been stated in section 5.6, the deviation of EFEM results for crop production structure from respective census information must not exceed 20%. Table 25 shows that the ratios of areas under certain plants are well represented. Small difference from statistics can be explained by the fact that areas not under arable farming and pastures are assigned to arable areas and grasslands in EFEM. Additionally, the character of EFEM as an economic optimization model explains the deviations from census. Hence, small advantages in crop prices and production costs often lead to changes in optimal solution in favour of certain crop.

Comparatively high is the divergence of modelling results from census data for silage maize and forage crops by livestock intensive Lower Saxony and regions with big farm size and high livestock numbers per farm, e.g., Brandenburg. However, for cereal crops, tubers, and oil plants the deviations are minimal, i.e., in average up to 9%. There are slight overestimations, namely 1.5%, by clover-grass in Brandenburg and Lower Saxony. It is compensated through the underestimation of areas under silage maize, more costly comparing to clover-grass, by ca. 0.2-3.7% (Table 25).

In the case of livestock husbandry, number of dairy cows is mainly underestimated due to economic optimization process. Thus, because of the integrated into the model option allowing to fulfil milk quota with less dairy cows having relatively high milk performance. However, a compensatory overestimation occurs by heifers, as due to the modelling restriction heifers have to be grown on the farm. This must assure full balancing of emissions analysed in this study (ZEDDIES *et al.*, 2011). Lower number of dairy cattle causes underestimation of areas under silage maize, a main forage crops for this animal category (Table 25).

6.3 Validation of Modelled Emissions

In this section emissions of NH_3 and PM resulting from the modelling procedure are validated. A proper validation of emission results can be assured through the comparison of EFEM emissions results with outputs of a reliable study. In this case we have chosen the official National Imission Inventory Report for Germany (NIR[32]) (DÄMMGEN *et al.*, 2009), an important element of climate modelling and policy assessment showing relative importance of various emission sources and demonstrating effects of each abatement measures on them. Presenting historic time-series of GHG and PM losses NIR projects these emissions for the year 2020. Outputs of NIR result from GAS-EM calculations (section 5.1). The validation procedure is performed through the comparison of emissions from agricultural production com-

[32] NIR – German National Emission Inventory

puted by EFEM and respective results of GAS-EM for the reference year 2003 (section 3.1). Regional capacities, emissions, and relative difference of the EFEM results from the GAS-EM outputs are shown in Table 26.

Table 26 Comparison of capacities and emissions resulting from EFEM and GAS-EM, for the year 2003

	Units	LS			BW			BB		
		NIR[1)]	**EFEM**	**%[2)]**	**NIR**	**EFEM**	**%**	**NIR**	**EFEM**	**%**
Main crops										
Winter grain	ha ($\times 10^3$)	780	825	**5.8**	317	317	**--**	457	477	**4.4**
Spring grain	ha ($\times 10^3$)	153	185	**20.9**	163	171	**4.9**	46.3	57.4	**24.0**
Maize	ha ($\times 10^3$)	94.9	89.1	**-6.1**	72.7	74.4	**2.3**	15.3	14.2	**-7.2**
Silage maize	ha ($\times 10^3$)	232	165	**-28.9**	68.8	66.6	**-3.2**	97.4	62.0	**-36.3**
Winter rapeseed	ha ($\times 10^3$)	85.1	113	**32.8**	67.5	67.5	**--**	103	138	**34.0**
Sugar beet	ha ($\times 10^3$)	114	114	**--**	20.6	20.4	**-1.0**	11.2	11.0	**-1.8**
Animal categories										
Dairy cows	ap*** ($\times 10^3$)	748	702	**-6.1**	398	339	**-12.5**	182	155	**-12.5**
Heifers	ap ($\times 10^3$)	864	641	**-25.8**	396	246	**-37.8**	205	171	**-16.9**
Bulls	ap ($\times 10^3$)	708	364	**-48.6**	187	91	**-51.6**	79	40	**-49.8**
Suckler cows	ap ($\times 10^3$)	74	72	**-2.7**	63	63	**0.2**	92	92	**--**
Sows	ap ($\times 10^3$)	659	659	**--**	300	300	**--**	102	102	**--**
Fattened pigs	ap ($\times 10^3$)	4,623	3,560	**-23.0**	984	653	**-33.6**	349	236	**-32.4**
Laying hens	ap ($\times 10^3$)	13,669	13,660	**-0.1**	2,567	2,657	**3.5**	2,435	2,632	**8.1**
Broilers	ap ($\times 10^3$)	28,628	28,415	**-0.7**	874	848	**-3.0**	3,295	3,295	**--**
PM emissions										
PM_{10} arable	tons PM_{10}	2,856	16,381	**474**	1,318	7,813	**493**	1,617	8,738	**440**
$PM_{2.5}$ arable	tons $PM_{2.5}$	110	3,138	**2,753**	51.0	1,493	**2,827**	62.0	1,628	**2,526**
PM_{10} livestock	tons PM_{10}	5,117	4,207	**-17.8**	1,121	834	**-25.6**	649	522	**-19.6**
$PM_{2.5}$ livestock	tons $PM_{2.5}$	1,086	861	**-20.7**	343	256	**-25.4**	151	138	**-8.6**
PM_{10} total	tons PM_{10}	7,973	20,588	**158**	2,439	8,647	**255**	2,266	9,260	**309**
$PM_{2.5}$ total	tons $PM_{2.5}$	1,196	3,999	**234**	394	1,749	**344**	213	1,766	**729**
NH_3 emissions										
NH_3 cattle[4)]	tons NH_3	62,710	54,087	**-13.8**	26,630	21,616	**-18.8**	14,390	13,492	**-6.2**
NH_3 pigs	tons NH_3	38,530	27,766	**-28.0**	10,150	7,222	**-28.8**	3,770	2,745	**-27.2**
NH_3 poultry	tons NH_3	11,260	8,100	**-28.1**	1,230	1,186	**-3.6**	1,650	1,306	**-20.8**
NH_3 min.fertil.[5)]	tons NH_3	17,000	9,063	**-46.7**	3,300	4,542	**37.6**	4,200	5,179	**23.3**
NH_3 total	tons NH_3	129,500	99,016	**-23.5**	41,310	34,566	**-16.3**	24,010	22,722	**-5.4**
GHG emissions										
CO_2	tons CO_2e ($\times 10^3$)	568	1,686	**197**	125	843	**574**	121	586	**384**
N_2O	tons CO_2e ($\times 10^3$)	4,592	5,088	**10.8**	1,806	2,294	**27.0**	1,100	1,965	**78.6**
CH_4	tons CO_2e ($\times 10^3$)	5,607	5,334	**-4,9**	2,110	2,340	**10.9**	1,058	1,287	**21.6**
GHG	tons CO_2e ($\times 10^3$)	10,767	12,108	**12.5**	4,041	5,477	**35.5**	2,279	3,838	**68.4**

Notes: [1)] NIR – National Imission Inventory report for Germany; [2)] – deviations of EFEM results from the NIR; [3)] ap – animal place; [4)] including NH_3 losses from pasture; [5)] NH_3 from mineral fertilizers' land application; LS – Lower Saxony, BW – Baden-Württemberg, BB – Brandenburg

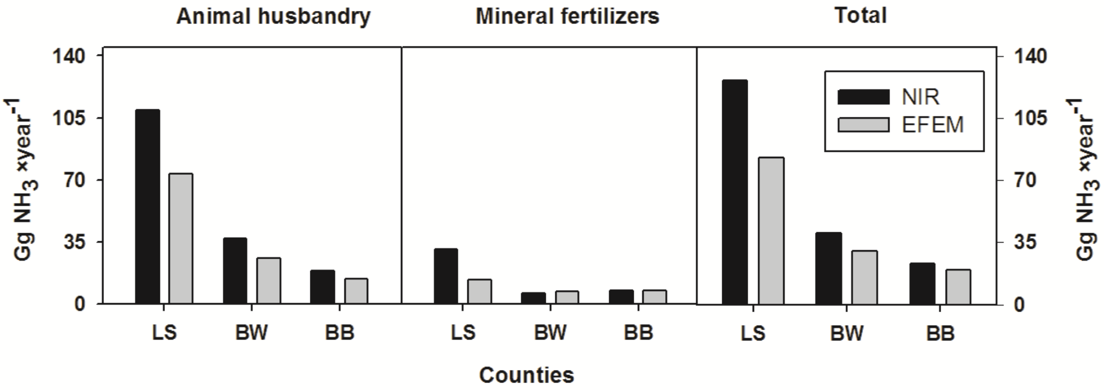
Sources: DÄMMGEN *et al.* (2009) and EFEM calculations

Emissions in the table are calculated as follows:

- For calculation of NH_3 and PM losses from livestock management, CH_4 emissions from enteric fermentation, and CH_4 and N_2O losses from manure storage following animal categories are taken: cattle (dairy cattle, calves, male beef bulls, and suckler cows), pigs (sows and fattened pigs), poultry (laying hens and broilers). Emissions of NH_3 from pastures are part of "NH_3 cattle".
- "NH_3 total" is the sum of NH_3 losses from animal husbandry and mineral fertilization.
- "$PM_{10}/_{2.5}$ arable" for EFEM comprises emissions from land tillage, yield harvesting, post-harvesting operations, burning of fuel and heating oil. The respective outputs in GAS-EM are the products of a given emission factor per hectare of arable area and land endowments.
- "PM total" is the sum of emissions results for "$PM_{10}/_{2.5}$ arable" and "$PM_{10}/_{2.5}$ animals".
- Emissions of CO_2 in EFEM are calculated as sum of losses from electricity use in animal barns, diesel burning by agricultural machinery and oil burning due to the yield drying. Carbon captured at the result of the sequestration process is not considered. In NIR total CO_2 emissions is the sum of losses from urea land application and liming in agriculture.
- N_2O comprises direct and indirect emissions and losses from manure storage. Methane (CH_4) is the sum of losses from enteric fermentation and manure storage.
- In GHG emissions sum up above mentioned losses of CH_4, N_2O, and CO_2.

Figures 12*a* and *b* show the two models' PM and NH_3 emission results aggregated into the source categories (i.e., livestock husbandry, arable farming, and total).

a)



b)

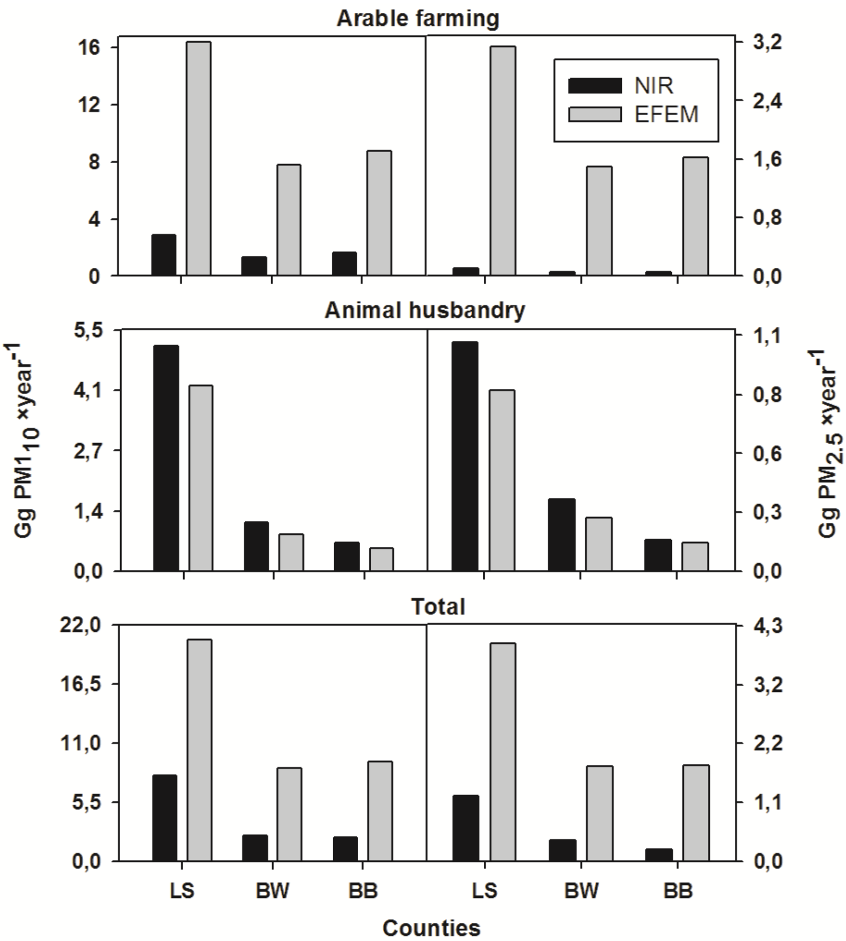


Figure 12 Comparison of EFEM and NIR modelling results for NH_3 (a) and PM (b) emissions

Notes: LS – Lower Saxony, BW – Baden-Württemberg, BB – Brandenburg, NIR – National Immission Report; EFEM- Economic Farm Emission Model

Sources: DÄMMGEN *et al.* (2009) and EFEM calculations

Figure 12*a* shows that NH_3 losses resulted from EFEM calculations are lower comparing to the NIR emissions. Controversially, EFEM results for PM emissions are higher, with exception of PM emissions from animal husbandry (Figure 12*b*). Emissions of GHGs resulting from EFEM tend to be overestimated comparing to the respective GAS-EM outputs, with the exception of CH_4 losses in Lower Saxony (Figure 12*c*).

Discrepancies between models' results occur, firstly, due to models' different characters and objectives (section 5.1). Thus, building up of the agricultural capacities by EFEM and GAS-EM is not alike. Land endowments and crop production structure modelled with GAS-EM are very close to the census data, with exception of overestimated areas under rye, oat, and maize. The respective EFEM results, contrary, deviate stronger from the census data, particularly for land under winter and spring grains and maize (Table 26). Moreover, if EFEM outputs differ slightly from census data due to the model optimizing character (section 5.4), GAS-EM results of are not adjusted during the modelling procedure.

Secondly, variations between resulting from two models animal capacities and emissions from livestock husbandry occur due to different categorization and aggregation of input data. Although number of animals modelled by GAS-EM is close to the respective census outcomes, in EFEM the outputs for heifers, bulls, fattened pigs, and laying hens is underestimated (Table 26). This mainly results from differences in aggregation of initial data in two models, and it is only partially caused by the optimization character of EFEM (section 5.4) (Tables 3 and 4 for EFEM and DÄMMGEN *et al.* (2009) for GAS-EM).

Thirdly, the dissimilarities between models' emission outputs occur due to contrasts in methodology for emission calculation. For instance, it is not clear, which operations of arable farming are contributing to the emission factor for PM from arable agriculture in GAS-EM. Controversially, in EFEM respective results are categorized into PM released from various sources, which emission intensities are defined for (see details above in the text of this section and section 5.2.4). In the case of NH_3 emission calculation, there are some differences in the implementation of the mass-flow approach caused by additional assumptions intended to improve the emission calculation methodology in EFEM, e.g., on seasonal NH_3 losses (section 5.2.5). This together with differences in aggregation and categorization explains lower NH_3 emissions from animal husbandry in EFEM (by 20%, 21%, and 11% for Lower Saxony, Baden-Württemberg, and Brandenburg, respectively). Emissions of CO_2 resulting from EFEM and GAS-EM are hardly comparable. Thus, in GAS-EM total CO_2 emissions comprise CO_2 released from urea land application and liming in agriculture, while the same emission category in EFEM comprises losses from more sources (see details above in the text of this section). In the case of CH_4 and N_2O emission calculation, the methodology slightly varies between EFEM and GAS-EM (for more information on EFEM see SCHÄFER (2006) and TRIEBE (2007) and on GAS-EM see DÄMMGEN *et al.* (2009)).

In general, the calculation of PM losses from arable agriculture is more disaggregated and process oriented in EFEM comparing to GAS-EM. Methodological approach for NH_3 calculation only slightly differs between two models due to additional assumptions in EFEM aimed to improve the approach making NH_3 emissions results closer to real ones. Emissions of GHGs resulted from EFEM are mainly overestimated comparing to respective GAS-EM outputs partially due to varying aggregation of input census information and partially at the result of differences in emission calculations methodology.

6.4 Effect of Different Political Conditions on Modelling Results

In order to determine the efficiency of various abatement options in the future, the projection of the reference year 2003 for the year 2015 has been performed (section 5.5). Modelling results for the reference scenario 2003 and BAU 2015 are presented in Table 27 and compared with each other in order to reveal the impact of different political conditions and modelling assumptions on the emissions (sections 5.5 and 5.6). One administrative region has been chosen for each Lower Saxony and Baden-Württemberg, i.e., Hannover and Stuttgart, respectively, for presentation and comparison of modelling outputs at the farm level (Table 27). The table shows absolute results for gross margin, PM, NH_3, and GHG emissions for the reference year and BAU.

Table 27 Individual farms' modelling results for the reference scenario and BAU for Hannover and Lower Saxony (a), Stuttgart and Baden-Württemberg (b), and Brandenburg (c)

a)

	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	HA	LS
2003								
Gross margin	EUR/ha	841	1,296	3,372	1,662	835	1,221	1,372
NH_3 total	kg NH_3-N/ha	5.8	31.5	67.2	39.1	10.8	20.7	31.2
PM_{10} total	kg PM_{10}/ha	9.5	4.6	16.4	34.5	11.1	10.1	10.4
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.0	1.3	3.2	7.8	2.9	2.4	2.6
N_2O total	kg CO_2e/ha	2,099	1,806	2,569	2,856	2,606	2,261	2,158
CH_4 total	kg CO_2e/ha	--	3,327	1,296	1,128	411	1,118	2.057
CO_2 total	kg CO_2e/ha	742	861	4,651	3,166	1,228	1,378	1,582
GHG total	kg CO_2e/ha	2,841	5,993	8,516	7,149	4,245	4,756	5,796
2015								
Gross margin	EUR/ha	1,101	1,610	3,531	2,105	1,132	1,501	1,680
NH_3 total	kg NH_3-N/ha	7.2	32.3	67.7	40.6	13.1	22.2	33.5
PM_{10} total	kg PM_{10}/ha	10.6	4.9	19.9	35.9	12.7	11.4	12.0
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.4	1.3	3.9	8.1	3.2	2.7	2.9
N_2O total	kg CO_2e/ha	2,709	1,879	3,334	3,560	3,206	2,752	2,513
CH_4 total	kg CO_2e/ha	--	3,505	1,201	1,109	421	1,155	2,114
CO_2 total	kg CO_2e/ha	965	861	4,691	2,836	1,456	1,515	1,760
GHG total	kg CO_2e/ha	3,674	6,245	9,225	7,504	5,083	5,423	6,386

b)

	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	ST	BW
2003								
Gross margin	EUR/ha	769	1,443	2,504	1,306	1,045	1,266	1,069
NH_3 total	kg NH_3-N/ha	6.4	37.2	47.7	47.3	20.0	23.5	21.5
PM_{10} total	kg PM_{10}/ha	10.2	3.9	15.1	31.9	7.6	9.0	7.5
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.3	1.2	3.0	7.3	2.4	2.2	1.9
N_2O total	kg CO_2e/ha	2,682	1,621	2,861	2,833	1,587	2,171	1,932
CH_4 total	kg CO_2e/ha	--	3,802	734	1,889	2,226	1,569	1,666
CO_2 total	kg CO_2e/ha	1,240	819	3,409	2,325	998	1,427	1,243
GHG total	kg CO_2e/ha	3,922	6,243	7,004	7,046	4,811	5,167	4,841
2015								
Gross margin	EUR/ha	854	1,736	3,059	1,871	1,381	1,544	1,323
NH_3 total	kg NH_3-N/ha	6.3	39.9	47.6	46.2	20.0	24.0	21.9
PM_{10} total	kg PM_{10}/ha	10.7	3.8	13.9	32.8	7.9	9.1	7.8
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.4	1.1	2.8	7.5	2.3	2.2	1.9
N_2O total	kg CO_2e/ha	2,677	1,748	3,147	2,922	1,260	2,147	1,967
CH_4 total	kg CO_2e/ha	--	4,338	675	1,838	2,341	1,705	1,796
CO_2 total	kg CO_2e/ha	1,172	799	2,359	2,298	899	1,206	1,093
GHG total	kg CO_2e/ha	3,849	6,884	6,180	7,058	4,500	5,058	4,856

c)

	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB
2003							
Gross margin	EUR/ha	521	914	4,421	19,574	697	738
NH_3 total	kg NH_3-N/ha	4.4	25.3	106	713	13.0	14.1
PM_{10} total	kg PM_{10}/ha	8.7	3.1	24.2	367	6.8	8.0
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	1.8	1.0	4.7	115	1.6	1.9
N_2O total	kg CO_2e/ha	1,581	1,199	4,446	32,244	1,679	1,683
CH_4 total	kg CO_2e/ha	--	2,660	1,321	17,328	1,098	970
CO_2 total	kg CO_2e/ha	630	586	7,291	58,229	753	882
GHG total	kg CO_2e/ha	2,212	4,445	13,058	107,801	3,530	3,535
2015							
Gross margin	EUR/ha	686	1,089	7,021	25,211	841	923
NH_3 total	kg NH_3-N/ha	5.9	25.0	104	825	14.7	15.7
PM_{10} total	kg PM_{10}/ha	10.8	3.3	23.1	441	8.3	9.7
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.2	0.9	4.5	129	1.9	2.2
N_2O total	kg CO_2e/ha	2,119	1,320	4,448	33,196	2,154	2,132
CH_4 total	kg CO_2e/ha	--	2,800	1,131	16,779	1,222	1,051
CO_2 total	kg CO_2e/ha	819	562	6,891	69,105	917	1,055
GHG total	kg CO_2e/ha	2,938	4,681	12,470	119,079	4,294	4,239

Notes: AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; HA – Hannover, ST – Stuttgart, BB – Brandenburg, LS – Lower Saxony, BW – Baden-Württemberg.

Table 28 demonstrates gross margin and emission results of the reference scenario and BAU 2015 for study regions and their administrative units.

Table 28 Modelling results for the reference scenario and BAU for Lower Saxony (a) and Baden-Württemberg (b), their administrative regions, and Brandenburg (b)

a)

	Units	BS	HA	LÜ	WE	LS
2003						
Gross margin	EUR/ha	1,008	1,221	1,193	1,755	1,372
NH_3 total	kg NH_3-N/ha	10.9	20.7	27.3	48.5	31.2
PM_{10} total	kg PM_{10}/ha	8.9	10.1	7.3	13.9	10.4
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.0	2.4	1.8	3.7	2.6
N_2O total	kg CO_2e/ha	2,214	2,261	1,966	2,246	2,158
CH_4 total	kg CO_2e/ha	558	1,118	2,130	3,106	2,057
CO_2 total	kg CO_2e/ha	968	1,378	1,146	2,318	1,582
GHG total	kg CO_2e/ha	3,740	4,756	5,242	7,670	5,796
2015						
Gross margin	EUR/ha	1,199	1,501	1,448	2,175	1,680
NH_3 total	kg NH_3-N/ha	12.2	22.2	29.1	52.3	33.5
PM_{10} total	kg PM_{10}/ha	9.7	11.4	8.5	16.2	12.0
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.3	2.7	2.0	4.1	2.9
N_2O total	kg CO_2e/ha	2,725	2,752	2,234	2,538	2,513
CH_4 total	kg CO_2e/ha	572	1,155	2,242	3,153	2,114
CO_2 total	kg CO_2e/ha	1,093	1,515	1,318	2,550	1,760
GHG total	kg CO_2e/ha	4,389	5,423	5,794	8,240	6,386

b)

	Units	ST	KR	FR	TÜ	BW	BB
2003							
Gross margin	EUR/ha	1,266	762	797	1,199	1,069	738
NH_3 total	kg NH_3-N/ha	23.5	12.9	17.5	26.2	21.5	14.1
PM_{10} total	kg PM_{10}/ha	9.0	7.9	5.5	7.1	7.5	8.0
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.2	2.0	1.5	1.8	1.9	1.9
N_2O total	kg CO_2e/ha	2,171	1,902	1,455	2,038	1,932	1,683
CH_4 total	kg CO_2e/ha	1,569	904	1,524	2,234	1,666	970
CO_2 total	kg CO_2e/ha	1,427	1,185	1,796	1,266	1,243	882
GHG total	kg CO_2e/ha	5,167	3,990	3,960	5,538	4,841	3,535
2015							
Gross margin	EUR/ha	1,544	958	1,029	1,472	1,323	923
NH_3 total	kg NH_3-N/ha	24.0	13.5	17.5	26.9	21.9	15.7
PM_{10} total	kg PM_{10}/ha	9.1	8.8	6.0	7.4	7.8	9.7
$PM_{2.5}$ total	kg $PM_{2.5}$/ha	2.2	2.1	1.5	1.8	1.9	2.2
N_2O total	kg CO_2e/ha	2,147	2,051	1,484	2,089	1,967	2,132
CH_4 total	kg CO_2e/ha	1,705	986	1,610	2,412	1,796	1,051
CO_2 total	kg CO_2e/ha	1,206	1,063	1,606	1,148	1,093	1,055
GHG total	kg CO_2e/ha	5,058	4,101	3,965	5,649	4,856	4,239

Notes: BS – Braunschweig, HA – Hannover, LÜ – Lüneburg, WE – Weser-Ems, LS – Lower Saxony, ST – Stuttgart, KR – Karlsruhe, FR – Freiburg, TÜ – Tübingen, BW – Baden-Württemberg, BB – Brandenburg

The absolute values of gross margin increase by all farm types in BAU comparing to the reference year. This augmentation equates to ca. 23%, 22%, and 25% for Hannover, Stuttgart, and Brandenburg, correspondingly. The highest increase of gross margin in Hannover and Stuttgart is expected for mixed farms (36% and 43%, respectively). Although in Brandenburg farms specializing on the pig production reveal the uppermost raise in gross margin (59%). The financial gain grows with relatively small rate of 5% by farms with emphasise on pigs husbandry in Hannover, due to reduction of area under relatively expensive spring grain and maize and more land for cultivation of a cheaper rye. A moderate increase of gross margin of 11% by arable farms in Stuttgart can be explained by lower prices for sugar beet in 2015 comparing to 2003. The animal premium and milk quota elimination follows with relatively lower increase of gross margin of 19% by forage growing farms in Brandenburg.

Gross margin increases at the regional level in a similar way as for individual farms. The highest increase of gross margin in Lower Saxony is projected for Weser-Ems (24%), the region with intensive livestock farming. Gross margin growth rate is the uppermost for Baden-Württemberg's administrative regions with intensive poultry and cattle production, i.e., for Karlsruhe (26%) and Freiburg (29%), respectively. Higher livestock density expected in 2015 due to the elimination of the obligatory minimum for fallow land (section 5.5) explains the boost in financial gain by administrative regions with intensive livestock husbandry.

Over 30% of NH_3 is released from forage growing and pig producing farms in Hannover and Stuttgart, while nearly 50% of the respective emission in Brandenburg stems from mixed farms. Table 27 shows the increase of total NH_3 emissions for Hannover in 2015 comparing to 2003 by 7.2%, with the highest growth rate for arable and mixed farms (24% and 21%, respectively). Higher amount of NH_3 released from arable farms occurs due to the abolition of obligatory minimum for fallow lands and following increase the NH_3 emission potential from mineral fertilization. The total growth rate for NH_3 emissions in Stuttgart is negligible (2%) and results mainly from the forage growing farms activities, where emissions raise by 7% per farm. Changes in optimal solution justify drop in NH_3 losses by up to 2% by other farm types in Stuttgart (Table 27).

Among the study regions the growth rate of NH_3 losses is the uppermost in Brandenburg (9%) comparing to Lower Saxony (6%) and Baden-Württemberg (3%). Boost in livestock number in Tübingen in 2015 explains the highest increase of NH_3 losses (8%) stemming mainly from manure management. The elimination of obligatory minimum for fallow area and following increase of area under mineral fertilization may justify the uppermost enhancement rate for NH_3 losses in Braunschweig (10%) (Table 28).

The elimination of obligatory minimum for fallow area and resulting increase of the land under arable production and mineral fertilization explains relatively higher growth rate for PM released from arable farms in 2015 in Hannover, Stuttgart, and Brandenburg (16%, 5%, and 23%, respectively in average for both PM fractions). By the same reason PM emission increases with high rate by livestock intensive farms with the emphasis on pig production in Hannover, poultry production farms in Stuttgart, and mixed farms in Brandenburg (with 22%, 3%, and 20%, correspondingly, in average for PM_{10} and $PM_{2.5}$). However, PM losses by pig producing farms drop by 7% in Stuttgart and 4% in Brandenburg partially due to the elimination of obligatory minimum for fallow area and therefore more forage produced than purchased. Rise in PM emissions from animal husbandry in 2015 comparing to 2003 can be explained by the higher number of animals in 2015 resulted from the economic optimization procedure.

At the level of federal state, PM losses rise with the uppermost rate for Weser-Ems and Lüneburg (ca. 14% in average for PM_{10} and $PM_{2.5}$) in Lower Saxony und Karlsruhe (nearly 8% in average for both PM fractions) in Baden-Württemberg. In Karlsruhe enhancement in PM released from animal husbandry and particularly intensive poultry production is bound with the banning of cage housing systems starting from 2009 and poultry housing in aviary.

Similarly to the PM and NH_3 emissions, higher GHG losses are projected for the year 2015 comparing to the reference situation in Hannover and Brandenburg (by 14% and 20%, respectively). However, amount of GHG released from farms in Stuttgart decreases by slightly over 2%. As it is shown in Tables 27 and 28, CO_2 emissions from upstream sector contribute the major to augmentations in GHG losses for Hannover and Brandenburg and to their decline for Stuttgart. Thus, the total GHG emissions increase in 2015 by 10% in Lower Saxony and 20% in Brandenburg due to the positive changes in CO_2, i.e., by 11% and 20% in Lower Saxony and in Brandenburg, respectively. However, due to an increase of livestock number, extensive fodder production and more agricultural land under prevailing manure land application CO_2 losses drop by ca. 12% and CH_4 emissions increase by 8% and the total GHG boost in Baden-Württemberg only by 0.5%. In general, alterations in GHG losses are uneven, thus, in Stuttgart amount of GHG released from agriculture declines by ca. 2% and it increases in Karlsruhe with the uppermost ratio in the federal state (by nearly 3%). Abolishment of the required obligatory minimum of fallow area and resulting extension of land under arable agriculture in BAU explains the boost in direct, indirect and total N_2O losses by 27% in Brandenburg, 16% in Lower Saxony, and 2% in Baden-Württemberg (Table 28).

Summing up it can be noticed that total emissions of PM, NH_3, and GHG at the farm and regional level in BAU depend on the prevailing production directions. Beside this, increase of agricultural area under both synthetic and organic fertilization, due to the elimination of the obligatory minimum of fallow land, and boost in livestock number, comparing to the reference scenario, determine alterations in emissions of above-mentioned pollutants in BAU.

6.5 Sensitivity Analysis

The aim of sensitivity analysis is to show, how reference results for PM losses change, when different emission intensities are taken for the modelling procedure. This is important to consider during the elaboration of the emission abatement strategy.

Losses of PM from soil tillage and crop harvesting are analysed in this section. While emission results in EFEM are calculated with mean values of PM emission factors for above-mentioned emission sources, minimal and maximal PM emission intensities have been additionally integrated into the model to perform the sensitivity analysis. Resulting minimal, maximal, and mean emissions from harvesting and tillage operations for the reference year have been compared between each other.

Availability of several emission factors for the same type of agricultural operations can be explained by the vulnerability of aspects responsible for the uncertainty of emission potential. Thus, in the case of tillage mainly soil and weather conditions determine variations in PM emission intensity. For instance, relatively higher amount of PM is released from sandy soils and/or by dry weather conditions. Controversially, tillage of clay or humid soil causes very negligible PM losses. As during combine harvesting PM is mainly released from crops, PM emission intensity from harvesting operations depends only on the weather before harvesting, and thereafter on moisture of harvested seeds. Emission intensities taken for the sensitivity analysis are presented in Table 29; their choice, particularities of measurement and calculation are discussed in details in section 5.2.4.

Table 29 PM emission factors for the simulation of PM losses in the framework of sensitivity analysis

		PM_{10}			$PM_{2.5}$		
		min	*mean*	*max*	*min*	*mean*	*max*
Harvesting[1)]	kg ton^{-1}	0.10	0.24	0.44	0.05	0.19	0.88
Plouging[2)]	kg ha^{-1}	1.20	6.10	11.00	0.10	0.68	1.30

Sources: [1)] HINZ (2004), HINZ *et al.* (2006) and HOEK *et al.* (2007) ; [2)] FUNK *et al.* (2005)

Figure 13 shows variations of total PM emissions resulting from the simulation at the level of administrative regions and federal states.

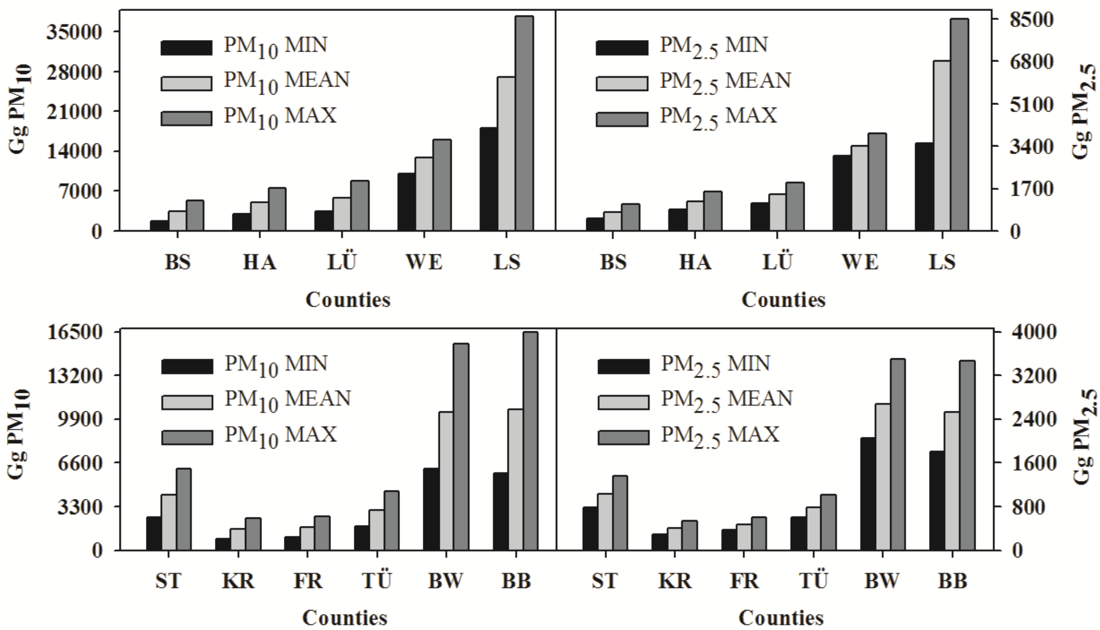


Figure 13 PM emissions (in Gg) resulting from the integration of different PM emission intensities for harvesting and ploughing into EFEM, for Lower Saxony, Baden-Württemberg, their administrative regions and Brandenburg

Notes: MIN, MEAN and MAX – minimal, mean and maximal values of PM emission factor

Integration of maximal or minimal PM emission factors into EFEM demonstrates the uppermost alterations of PM losses in study regions with prevailing arable farming. Thus, in Brandenburg and Baden-Württemberg PM is mainly released from tillage and harvesting operations. Growth rate for PM losses due to the introduction of the maximal PM emission intensity into EFEM reaches 55% for PM_{10} and 37% and for $PM_{2.5}$ in Brandenburg and 49% and 31% for PM_{10} and $PM_{2.5}$, correspondingly, in Baden-Württemberg. The reduction rate, resulting from the calculation of PM emissions with minimal emission factors is again the uppermost in Brandenburg (45% for PM_{10} and 29% for $PM_{2.5}$) and only slightly less in Baden-Württemberg (41% for PM_{10} and 24% for $PM_{2.5}$). The respective outputs for Lower Saxony are comparatively lower due to a prevailing livestock management, revealing the increase of 39% for PM_{10} and 25% for $PM_{2.5}$, respectively and the reduction of 33% and 22% for PM_{10} and $PM_{2.5}$, correspondingly.

Among administrative regions, the dominating arable character of agricultural activities explains the uppermost augmentation of PM losses in Karlsruhe (53% for PM_{10} and 34% for $PM_{2.5}$) and Braunschweig (60% and 43% for PM_{10} and $PM_{2.5}$, respectively) due to the emission calculations with the maximal PM emission intensities. The lowest raise in PM losses occurs in study regions with prevailing livestock farming, i.e., Weser-Ems (25% for PM_{10} and 15% for $PM_{2.5}$) and Stuttgart and Freiburg (ca. 48% and 29% for PM_{10} and $PM_{2.5}$, correspondingly). Alternatively, emissions calculations with minimal emission factors reveal the highest PM emission abatement in Braunschweig (50% for PM_{10} and 33% for $PM_{2.5}$) and Karlsruhe (45% and 26% for PM_{10} and $PM_{2.5}$, respectively) and the lowest in Weser-Ems (21% for PM_{10} and 12% for $PM_{2.5}$) and Freiburg (41% for PM_{10} and 22% for $PM_{2.5}$).

Figure 14 shows, how the contribution of main PM sources to the total PM losses change at the regional level depending on a chosen PM emission intensity.

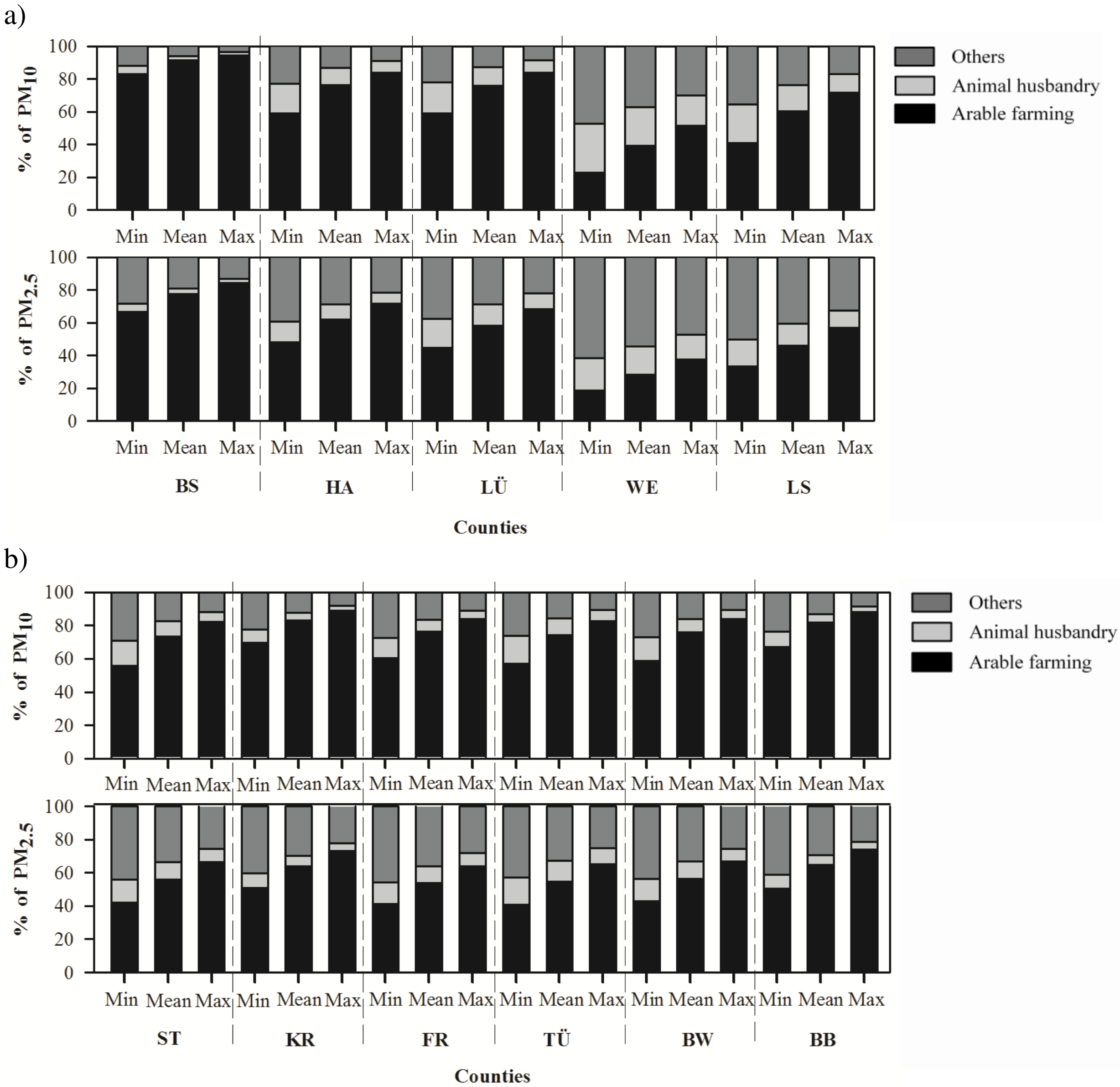


Figure 14 Shares of PM emissions from arable farming, animal husbandry and other sources (i.e., diesel and heating oil burning and upstream sector) in the total PM losses for Lower Saxony (a), Baden-Württemberg (b), their administrative regions and Brandenburg (b)

Notes: BS – Braunschweig, HA – Hannover, LÜ – Lüneburg, WE – Weser-Ems, LS – Lower Saxony, ST – Stuttgart, KR – Karlsruhe, FR – Freiburg, TÜ – Tübingen, BB – Brandenburg

Both Figures 13 and 14 demonstrate a direct connection between changes in emission results from implementation of different PM emission intensities and a character of agricultural management prevailing. Thus, livestock intensive regions (i.e., Weser-Ems, Stuttgart, and Tübingen) response relatively weak to the introduction of different PM emission factors for harvesting and ploughing into the model. Controversially, regions with intensive arable production (e.g., Braunschweig and Karlsruhe) demonstrate stronger alterations in PM losses.

7 QUANTITATIVE ANALYSIS OF ABATEMENT OPTIONS

More is known about, how the exposure to aerial pollutants affects the health of animals and stockmen. However, a wide spectrum of available relevant information has to be in tact with the actions in elaboration of new emission abatement strategies. In this chapter, different common and relatively new farming practises resulting in lower NH_3 and PM losses are checked for their emission mitigation efficiency. The idea of the model simulations or scenarios is both cost-benefit analysis of the environmental programs and the quantitative assessment of abatement option's effect on the environment (cost-effectiveness analysis).

7.1 Abatement of NH_3 Emission: Abdication of Urea from Mineral Fertilization Practises (Scenario I)

Mineral fertilization is an important mean to maintain soil nutrients content and ensure a proper nutritional value of economic crops, when there is not enough organic manure available. However, application of fertilizers, particularly urea, to agricultural soils results in relatively high NH_3 emission. Beside environmental concern, the **Scenario I** implementation intends to increase production efficiency, which may decline due to plant diseases occurring from urea land application and following urea hydrolysis boosting soil pH and making it conductive for some fungus (HILL *et al.*, 2003).

The *scenario* objective is to determine environmental and financial efficiency of the urine exclusion from mineral fertilization practise through the comparison of the scenario outputs with the BAU results. Calcium ammonium nitrate and urea are taken for the analysis because of their comparatively high share in domestic sales, i.e., 41.3% and 18.7%, correspondingly. Other mineral fertilizers are not so wide applicable in Germany (STATISTISCHES JAHRBUCH, 2007). Additionally, types of land management, such as arable land or grassland, are considered by calculation of NH_3 amount released due to mineral fertilization, as the difference in land management boosts the climatologic discrepancy affecting NH_3 emissions.

Mineral fertilizers' prices for 2015 integrated into EFEM result from the regression analysis for annual values calculated as arithmetic average of monthly prices for calcium ammonium nitrate and urea in Germany. Monthly prices are taken for 9 years (from 2001 to 2009) from DLZAGRARMAGAZIN (2010). Before being implemented into the model prices have been recalculated into EUR per kg of mineral N. Due to the lack of information on the applicability of certain fertilizers in Germany, their annual prices and NH_3 emission intensities have been weight with their domestic sales values, resulting from the regression analysis from 1993 to 2008, and presented in Table 30.

Table 30 Nitrogen content in fertilizers (in %), NH_3 emission factors (in kg NH_3-N kg N^{-1}), values of domestic sales (in 1000 tonnes) for mineral fertilizers

	N-content, in %[1)]	**Emission factors, in kg NH_3-N kg N^{-1}**		**Fertilizers' domestic sales, in 1000 t**		**Fertilizers' prices, in EUR per kg fertilizer**		**Fertilizers' prices, in EUR per kg N in fertilizer**	
		Arable land[2)]	**Grass-land[3)]**	**2003[3)]**	**2015[4)]**	**2003**	**2015**	**2003**	**2015**
Calcium ammo-nium nitrate	27.0	0.006	0.016	835	462	14.3	31.8	55.1	122
Urea	46.0	0.115	0.230	308	445	17.7	38.7	38.0	83.1

Sources: [1)] LfL (2003)[2)] Dämmgen *et al.* (2009); [3)] Statistisches Jahrbuch (2007); [4)] own calculations based on Statistisches Jahrbuch (2007)

The **Scenario I** outputs compared to the BAU results are shown in Table 31 and Appendixes I, II, and III. Relatively high amount of agricultural land available became a selection criterion for the administrative units, which the *scenario* outcomes are demonstrated for (Table 31).

Table 31 Average emissions occurring from abdication of urea from mineral fertilization practise by different farm types in Hannover and Lower Saxony (a), Freiburg and Baden-Württemberg (b), and Brandenburg (c)

a)

Categories \ Farm type	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	HA	LS
Agricultural area	ha (×10^3)	145	122	48.3	12.5	164	492	2,599
Livestock density	LU/ha[1)]	--	1.0	2.1	0.9	0.2	0.5	0.9
Scenario results								
Gross margin	EUR/ha	1,051	1,604	3,517	2,078	1,103	1,486	1,670
NH_3 total	kg NH_3-N (×10^3)	165	3,728	3,190	442	1,266	8,791	78,300
Changes to the reference								
N fertilizers applied	%	-17.8	-6.2	-13.4	-1.6	-1.6	-5.3	-5.8
Gross margin	%	-0.5	-0.4	-0.4	-1.3	-2.6	-1.0	-0.6
PM_{10} total	%	-0.2	-0.5	0.0	0.0	-0.1	-0.1	-0.1
$PM_{2.5}$ total	%	-0.6	-1.4	-0.4	-0.1	-0.2	-0.5	-0.1
NH_3 organic[2)]	%	--	1.9	-0.1	--	--	0.8	-0.5
NH_3 mineral[3)]	%	-88.5	-82.9	-79.8	-82.0	-82.0	-84.7	-84.6
N_2O total	%	-4.2	-2.3	-5.7	-1.2	-1.4	-2.9	-2.9
CH_4 total	%	--	0.2	--	--	-12.7	-1.4	-0.1
CO_2 total	%	-2.2	-1.9	-0.5	-0.3	-0.8	-1.1	-0.7
GHG total	%	-3.6	-0.8	-2.3	-0.7	-2.2	-2.0	-1.4
Average abatement costs								
NH_3 total	EUR/kg NH_3-N	0.6	2.1	6.2	3.4	3.6	2.3	2.4

b)

Categories \ Farm type	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	FR	BW
Agricultural area	ha ($\times 10^3$)	48.4	173	11.2	1.4	81.1	315	1,404
Livestock density	LU/ha[1)]	--	0.6	1.4	1.2	0.6	0.5	0.7
Scenario results								
Gross margin	EUR/ha	639	1,118	2,333	8,280	700	1,012	1,312
NH_3 total	kg NH_3-N ($\times 10^3$)	65.7	3,544	490	220	834	5,154	28,186
Changes to the reference								
N fertilizers applied	%	-10.4	-11.7	-20.2	-11.9	-9.1	-10.5	-13.8
Gross margin	%	-3.4	-0.2	-0.4	-0.1	-1.6	-0.8	-0.8
PM_{10} total	%	-0.1	-1.3	0.2	--	0.1	-0.3	0.4
$PM_{2.5}$ total	%	-0.5	-1.7	-0.5	--	-0.5	-0.8	0.1
NH_3 organic[2)]	%	--	--	--	--	--	--	0.5
NH_3 mineral[3)]	%	-82.5	-83.9	-85.4	-83.7	-83.0	-83.0	-82.9
N_2O total	%	-3.7	-2.5	-7.2	-2.3	-4.7	-3.8	-3.8
CH_4 total	%	--	--	--	--	--	--	-0.1
CO_2 total	%	-1.4	-1.0	-0.4	-0.2	-2.9	-1.4	0.3
GHG total	%	-2.9	-0.8	-3.1	-0.6	-2.8	-1.7	-1.5
Average abatement costs								
NH_3 total	EUR/kg NH_3-N	3.5	3.2	3.0	3.3	3.4	3.4	3.6

c)

Categories \ Farm type	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB
Agricultural area	ha ($\times 10^3$)	446	168	8.5	3.5	700	1,326
Livestock density	LU/ha[1)]	--	0.8	3.4	16.4	0.4	0.4
Scenario results							
Gross margin	EUR/ha	680	1,086	7,021	25,196	826	911
NH_3 total	kg NH_3-N ($\times 10^3$)	393	4,065	882	2,836	8,194	16,370
Changes to the reference							
N fertilizers applied	%	-24.3	-11.0	--	--	-8.5	-10.5
Gross margin	%	-0.9	-0.3	--	--	-1.8	-1.3
PM_{10} total	%	-0.2	-0.2	--	--	0.1	0.0
$PM_{2.5}$ total	%	-0.9	-0.6	--	--	-0.4	-0.5
NH_3 organic[2)]	%	--	--	--	--	3.0	1.3
NH_3 mineral[3)]	%	-88.6	-83.7	--	--	-83.3	-85.1
N_2O total	%	-7.8	-2.8	--	--	-5.5	-5.7
CH_4 total	%	--	0.0	--	--	2.9	1.8
CO_2 total	%	-3.7	-1.2	--	--	-2.2	-2.1
GHG total	%	-6.6	-0.9	--	--	-2.3	-2.9
Average abatement costs							
NH_3 total	EUR/kg NH_3-N	0.9	3.2	--	--	3.7	2.6

Notes: [1)] LU/ha – livestock units per hectare; [2)] NH_3 losses from manure management; [3)] NH_3 losses from application of mineral fertilizers; AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; HA – Hannover, LS – Lower Saxony, FR – Freiburg, BW – Baden-Württemberg, and BB – Brandenburg

Although the price per kg of urea is higher than per 1 kg of calcium ammonium nitrate, the price per 1 kg urea-N is relatively lower due to higher urea N-content, i.e., nearly 47% comparing to 26% in calcium ammonium nitrate. This explains the reduction of the gross margin by all study regions and all farm types resulting from the *scenario* implementation. The gross margin reduction reaches ca. 0.6–1.3%, with the highest rates for arable farms in Freiburg and Baden-Württemberg (over 3.4%), mixed farms in Hannover and Lower Saxony (2.6%), and poultry producing intensive livestock farms in Brandenburg (ca. 2%) (Table 31).

The substitution of urea with calcium ammonium nitrate leads to the reduction of NH_3 emission from mineral fertilization by nearly 90% (Table 31), although the mitigation of total NH_3 losses is comparatively low, i.e., 27%, 24%, and 12% for Brandenburg, Hannover, and Freiburg, respectively. The strongest positive effect of the scenario implementation on the total amount of NH_3 released from agriculture in Brandenburg can be explained by the inferior livestock density (0.4 LU ha^{-1}) and thereafter a higher demand for mineral fertilizers in this federal state. Nevertheless, 18%-increase of fertilizers' price leads to a higher fertilizer replacement value of manure and thus, to less mineral fertilizers applied. Hence, in Hannover and Brandenburg much less fertilizers have been applied onto the land at arable farms (by ca. 18% and 24%, correspondingly) and in Freiburg at pig producing farms (by nearly 20%). This also results in changes of optimal solution for winter rye, winter rapeseed, and sunflowers in favour of crops with fewer N-requirements. Less of fertilizers applied onto agricultural land together with relatively low NH_3 emission intension of fertilization without urea lead to the NH_3 abatement by ca. 89% for arable farms in Hannover and Brandenburg and by about 85% pig producing farms in Freiburg. At the level of federal state, reduction of NH_3 emission from mineral fertilizers land application occurring due to the implementation of **Scenario I** reaches 85% in Brandenburg and Lower Saxony and 83% in Baden-Württemberg.

Scenario conditions cause alterations in optimal solution and hence both positive and negative negligible changes in PM losses. Exclusion of urea from fertilization practises leads to less fertilizers applied onto the land and therefore lower GHG emissions by all farm types and regions, with uppermost emission diminution rate for Brandenburg (by ca. 3%). Mainly abatement of N_2O stemming from fertilizers production and application explains GHG reduction.

Abatement of NH_3 emissions is the cheapest in the regions with a higher emission reduction rate, namely in Hannover, Lower Saxony, and Brandenburg (2.3, 2.4, and 2.6 EUR/kg NH_3-N, correspondingly) and the most expensive for the regions with a relatively low NH_3 emission reduction, i.e., in Freiburg and Baden-Württemberg (3.4 and 3.6 EUR/kg NH_3-N, respectively). At the farm level, average costs for NH_3 abatement are the uppermost for mixed farms in Brandenburg (up to 3.7 EUR/kg NH_3-N), intensive pig producing farms in Hannover (ca. 6.2 EUR/kg NH_3-N), and arable farms in Freiburg (3.5 EUR/kg NH_3-N). Higher mitigation costs result from lower reduction of the total NH_3 losses. The fact that manure exchange function has not been considered by the modelling procedure for Baden-Württemberg, still an increasing need for mineral fertilizers and thus relatively high gross margin reduction explain costly NH_3 emission mitigation by arable farms in Freiburg.

In general, it must be mentioned that abdication of urea from mineral fertilization practise is efficient measure for reduction of NH_3 released. Beyond this, scenario has a negative effect for GHG emission development. The most efficient emission abatement occurs in the regions and at the farms with larger land endowments, lower livestock density and thus higher amount of mineral fertilizers applied.

7.2 Abatement of NH_3 Emissions: Change of Housing System (Scenario II)

Within **Scenario II** it has been switched from slurry to solid manure based livestock housing system. The *scenario* objective is to check, to which extend NH_3 emission can be reduced, under which costs and side effects for other pollutants. The main *scenario* condition is that all cattle are housed on the (deep) litter and pigs and poultry - in liquid manure based systems (section 5.6).

The change from solid to slurry based livestock management requires additional expenses, varying depending on animal barn and adjustments performed. As this makes an estimation of the total costs for modification of already existing livestock house problematic, it is assumed that solid manure system is introduced in a new-built livestock house. In Table 32 straw amount, costs for manure spreading, and levels of N and NH_4 are compared between two livestock housing systems. As the table shows, additional expenses from introduction of solid manure based system in a new built animal house occur mainly due to the purchase of straw for floor bedding, and more expensive solid manure land application. Regardless comparatively higher content of total N in solid manure, amount of NH_4-N, easily breakable into NH_3, and therefore NH_3 emission potential are lower.

Table 32 Crucial EFEM assumptions for solid and slurry based housing systems

		Units	Solid manure system	Liquid manure system
Straw amount[1)]	dairy cows	100 kg/LU	1.0	--
	bulls and heifers	100 kg /LU	1.5	--
	calves	100 kg /LU	0.3	--
Straw price		EUR/100 kg	8.6	8.6
N content[2)]	dairy cows		6.5	3.8
	heifers		4.3	3.8
	suckler cows		6.0	5.5
	calves & male cattle	kg N/t (m^3)	5.0	4.8
NH_4 content[2)]	dairy cows		2.1	2.3
	heifers		1.8	2.3
	suckler cows		2.1	3.4
	calves & male cattle	kg NH_4-N/t (m^3)	2.1	3.1
Costs of manure spreading		EUR/100kg (m^3)	4.4**	4.1***
NH_3 reduction due to manure land application		%	--	by up to 12****

Notes: *for straw spreading and excreta removing, **average for three study regions, ***costs have been calculated based on the frequency distribution assumptions for manure spreading techniques in BAU (section 5.6) in average for three regions; **** NH_3 reduction has been calculated based on assumptions for occurrence of manure spreading techniques in BAU (section 5.6).

Sources: 1) KTBL (1998); 2) LFL (2008); 3) KTBL (2002)

The switch from slurry based to deep litter based livestock management system is not a subject to financial aid and limitations; exception is the common for all study regions restriction on N-input to agricultural land (LFL, 2008). As the *scenario* application is restricted within cattle management, a relatively higher cattle number has become the selection criterion for administrative regions for the *scenario* results presentation. Number of cattle places as well as **Scenario II** outputs are extrapolated to the regional level and presented in comparison to the BAU results in Table 33 and Appendixes I, II, and III.

Table 33 Results of the switch from slurry to solid manure based housing system at farms in Lüneburg and Lower Saxony (a), Tübingen and Baden-Württemberg (b), and Brandenburg (c)

a)

Categories \ Farm type	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	LÜ	LS
Number of animals								
Dairy cows	ap[1)]	--	262,508	--	--	--	262,508	746,057
Suckler cows	ap	--	8,468	--	--	18,216	26,684	72,492
Male cattle[2)]	ap	--	101,616	--	--	11,592	113,208	361,637
Heifers	ap	--	114,318	--	--	14,904	129,222	364,237
Scenario results								
Gross margin	EUR/ha	930	1,513	5,160	935	1,079	1,405	1,638
PM_{10} total	kg PM_{10} ($\times 10^3$)	1,790	1,851	1,039	1,055	1,181	6,916	32,090
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times 10^3$)	390	512	204	242	316	1,665	7,826
NH_3 total	kg NH_3-N ($\times 10^3$)	108	13,186	3,744	764	1,602	20,374	80,843
Changes to the reference								
Gross margin	%	--	-5.0	--	--	--	-2.9	-2.5
PM_{10} arable	%	--	1.2	--	--	--	0.3	0.2
$PM_{2.5}$ arable	%	--	2.4	--	--	--	0.7	0.3
PM_{10} animal	%	--	10.1	--	--	--	2.5	1.1
$PM_{2.5}$ animal	%	--	9.8	--	--	--	5.4	3.2
NH_3 organic[3)]	%	--	-19.7	--	--	--	-14.9	-9.1
NH_3 mineral[4)]	%	--	-3.3	--	--	--	-0.6	0.4
N_2O total	%	--	-15.4	--	--	--	-6.4	-4.0
CH_4 total	%	--	-14.9	--	--	--	-13.6	-12.6
CO_2 total	%	--	-9.2	--	--	--	-2.9	-0.8
GHG total	%	--	-14.4	--	--	--	-8.4	-6.0
Average abatement costs								
NH_3 total	EUR/kg NH_3-N	--	10.9	--	--	--	10.9	15.3

b)

Categories \ Farm type	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	TÜ	BW
Number of animals								
Dairy cows	ap[1)]	--	161,613	--	--	16,349	177,962	399,073
Suckler cows	ap	--	10,316	--	--	2,515	12,831	63,316
Male cattle[2)]	ap	--	27,509	--	--	1,258	28,766	90,662
Heifers	ap	--	55,017	--	--	10,061	65,078	162,888
Scenario results								
Gross margin	EUR/ha	760	1,499	8,146	1,142	1,533	1,422	1,292
PM_{10} total	kg PM_{10} ($\times 10^3$)	1,371	890	220	464	455	3,400	11,381
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times 10^3$)	313	253	41.7	95.7	134	836	2,785
NH_3 total	kg NH_3-N ($\times 10^3$)	850	6,996	1,108	528	1,124	10,606	29,531
Changes to the reference								
Gross margin	%	--	-5.7	--	-0.2	-1.6	-3.4	-2.4
PM_{10} arable	%	--	0.6	--	--	2.9	0.4	0.3
$PM_{2.5}$ arable	%	--	1.0	--	--	3.2	0.5	0.5
PM_{10} animal	%	--	8.9	--	--	1.4	2.8	2.2
$PM_{2.5}$ animal	%	--	8.7	--	--	2.7	5.4	4.4
NH_3 organic[3)]	%	--	-14.2	--	--	1.4	-10.6	-7.2
NH_3 mineral[4)]	%	--	11.1	--	--	38.0	3.8	5.0
N_2O total	%	--	-14.8	1.0	--	8.8	-5.2	-1.8
CH_4 total	%	--	-14.1	--	--	-12.7	-13.5	-12.9
CO_2 total	%	--	-4.6	-0.1	--	--	-1.4	-0.6
GHG total	%	--	-13.2	--	--	-3.5	-8.0	-5.6
Average abatement costs								
NH_3 total	EUR/kg NH_3-N	--	18.7	--	--	-25.7[5)]	20.2	22.4

c)

Categories \ Farm type	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB
Number of animals							
Dairy cows	ap[1)]	--	82,136	--	--	99,336	181,472
Suckler cows	ap	--	20,308	--	--	71,367	91,676
Male cattle[2)]	ap	--	21,211	--	--	18,324	39,535
Heifers	ap	--	14,442	--	--	71,367	85,809
Scenario results							
Gross margin	EUR/ha	686	1,036	7,024	25,207	812	901
PM_{10} total	kg PM_{10} ($\times 10^3$)	4,792	547	196	1,526	5,717	12,778
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times 10^3$)	980	158	38.0	445	1,327	2,948
NH_3 total	kg NH_3-N ($\times 10^3$)	2,627	3,778	882	2,836	9,637	19,760
Changes to the reference							
Gross margin	%	--	-4.9	--	--	-3.5	-2.4
PM_{10} arable	%	--	-3.1	--	--	-2.0	-1.2
$PM_{2.5}$ arable	%	--	-1.8	--	--	-2.1	-1.2
PM_{10} animal	%	--	8.5	--	--	4.7	1.3
$PM_{2.5}$ animal	%	--	8.3	--	--	4.5	3.0
NH_3 organic[3)]	%	--	-10.3	--	--	-12.5	-9.0
NH_3 mineral[4)]	%	--	-0.3	--	--	8.9	4.6
N_2O total	%	--	-12.1	--	--	3.9	1.1
CH_4 total	%	--	-12.9	--	--	-11.8	-11.6
CO_2 total	%	--	-3.2	--	--	11.2	4.9
GHG total	%	--	-11.5	--	--	1.0	-1.1
Average abatement costs							
NH_3 total	EUR/kg NH_3-N	--	21.3	--	--	31.9	27.3

Notes: [1)] ap – animal places; [2)] male cattle ≥1 year; [3)] NH_3 losses from manure management; [4)] NH_3 losses from mineral fertilization; [5)] no NH_3 emission reduction occurs; AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; LÜ – Lüneburg, LS – Lower Saxony, TÜ – Tübingen, BW – Baden-Württemberg, and BB – Brandenburg

Due to higher costs of solid manure based housing system (Table 32), the gross margin resulting from the *scenario* implementation decreases by 2.4-2.5% in total for all study regions with the highest rate for forage growing farms in Tübingen (ca. 6%) and Lüneburg and Brandenburg (nearly 5%). No changes in emissions occur due to the *scenario* implementation by mixed farms in Lüneburg, as according to modelling assumptions suckler cows and heifers there are initially situated in barns with solid manure management system (section 5.6).

The switch from slurry to solid manure based housing system has a negative effect for development of PM emissions from animal barn, as the livestock management with deep litter, especially by male cattle and heifers, releases more PM (section 5.2.4). Analysis of PM losses from livestock house at the regional level reveals the highest boost in PM losses in Tübingen and Baden-Württemberg (ca. 5% and 3% in average for PM_{10} and $PM_{2.5}$). Less is the increase of PM emissions for livestock intensive Lüneburg and Lower Saxony (nearly 3% for both PM fractions) and arable Brandenburg (ca. 1% for PM_{10} and 3% for $PM_{2.5}$).

Similarly to the PM development at the regional level, PM released from animal husbandry at the farm level increases with the uppermost rate by forage growing farms in Lüneburg (10.1 and 9.8% for PM_{10} and $PM_{2.5}$, correspondingly), Tübingen and Brandenburg (ca. 9% in average for both PM fractions). This can be explained by the fact that by nearly 90% total cattle places at these farms in Lüneburg are constituted by PM intensive bulls and heifers, while dairy cows and male cattle, also causing comparatively high PM emissions, represent ca. 64% and 11% of total livestock places at forage growing farms in Brandenburg.

Beside PM losses from livestock management, it is important to analyse the changes in PM released from arable farming. They result from alterations in crop production structure occurring due to the switch from slurry to solid manure based livestock housing systems and presented in Figure 15.

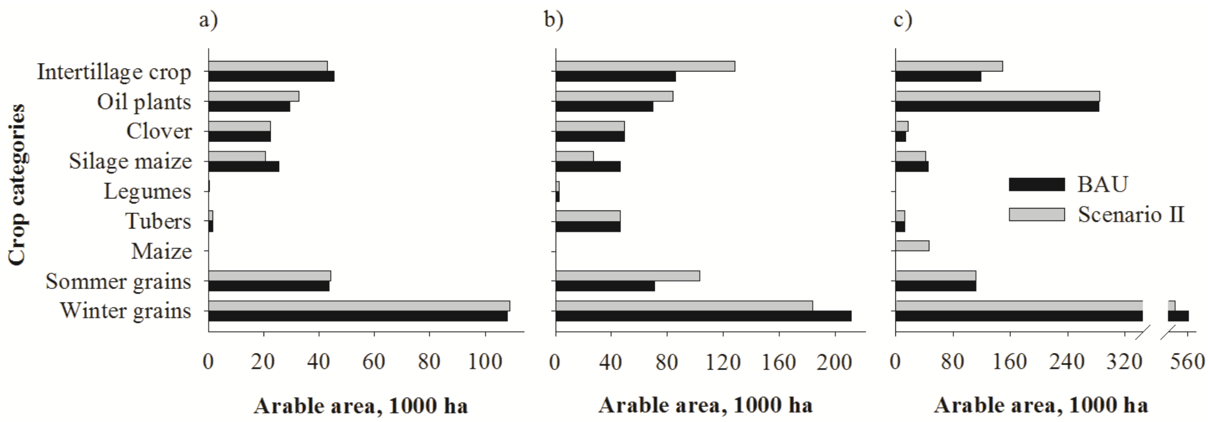


Figure 15 Crop production for **BAU** and **Scenario II** in Tübingen (a), Lüneburg (b), and Brandenburg (c)

Results demonstrated in Figure 15 reveal clear increase in PM from arable farming in Lower Saxony and Baden-Württemberg and their administrative regions. This can be explained by higher production of PM intensive cereal, maize, and oil plants. Thus, the area under winter grains in Lüneburg and Lower Saxony reduces (by ca. 13% and 3%, respectively). However, it is counterbalanced through more spring grains and oil crops produced in these regions, i.e., by nearly 20% and 46%, correspondingly, for Lüneburg and by 17% and 14%, respectively, for Lower Saxony). The later causes the boost in PM emissions by 0.3% for PM_{10} and 0.7% for $PM_{2.5}$ in Lüneburg and by 0.3% in average for both PM fractions in Lower Saxony. In Tübingen and Baden-Württemberg production of both winter grains increases (by 1.4% and 0.6%, correspondingly) as well as the area under cultivation of oil plants in Tübingen (by about 10%) and maize and oil crops in Baden Württemberg (by ca. 63% and 11%, respectively). Controversially in Brandenburg reduction of area under winter grains (by 8%) is more considerable comparing to the increase in maize and cover crops production (by ca. 45.5 ha and 30.3 ha, correspondingly), that results in 1.2% less PM emitted from arable farming (Figure 15 and Table 33).

Comparatively low NH_4-content per kg of solid manure explains reduction of NH_3 emitted from manure management and of total NH_3 losses (Table 32). Among the regions presented in Table 33, the uppermost reduction of total NH_3 is detected in Lüneburg (13%), comparing to Tübingen and Brandenburg (with 9% and 5%, respectively). At the farm level, the highest reduction rates for NH_3 losses from livestock management in Lüneburg and Tübingen is detected by forage growing farms (ca. 20% and 14%, correspondingly). In Brandenburg NH_3 abatement is more efficient by mixed farms (13%). Such considerable reduction of NH_3 released from forage growing and mixed farms corresponds with comparatively higher livestock number and hence increasing NH_3 emission and abatement potential, due to the *scenario* assumptions. In Tübingen a slight boost of the NH_3 released from the management of organic manure by mixed farms (+1.4%) can be explained by higher content of NH_4 in mineral fertilizers and pigs' liquid manure and lacking possibility to sell liquid manure through manure exchange. The later results in the excess of solid manure to be stored until the moment of land application; meanwhile emission abatement options applicable for storage of solid manure are limited (section 2.1.2.3). A need for counterbalancing of lower NH_4 content in solid manure with additional N is one of the reasons for a raise of NH_3 emissions from mineral fertilization in all study regions, with highest rate in Baden-Württemberg. Another explanation for it is the adjustment of the optimal solution to the *scenario* assumptions (Figure 15).

The overall reduction of GHG losses occurs mainly due to the abatement of CH_4 emissions from manure management (by 13% in Lower Saxony and Baden-Württemberg, and by 12% in Brandenburg), with the uppermost rate for forage growing farms. Total GHG emissions drop with the highest ratio in Lower Saxony and Baden-Württemberg (ca. 6%), while in Brandenburg respective reduction is negligible (nearly 1%).

Average costs for total NH_3 abatement through the change from slurry to solid manure based housing systems varies from 10.9 to 27.3 EUR per kg NH_3-N, with the highest costs attributed to the regions and farms with the least reduction of NH_3 released. Lower average costs for NH_3 mitigation in Lüneburg and Lower Saxony (10.9 and 15.3 EUR kg NH_3-N^{-1}, respectively) can be explained by lower NH_3 emission potential of solid manure applied onto agricultural land.

Overall, it can be said that the **Scenario II** implementation for a newly built livestock house has a positive effect for NH_3 and GHG emissions reduction, meanwhile leading to higher PM losses. The abatement efficiency varies depending on region and farm type; thus, relatively costly NH_3 abatement corresponds with the low livestock density and land endowments.

7.3 Abatement of NH_3 Emission: Protein Adjusted Feeding of Livestock (Scenario III)

An adjustment of animal fodder nutritional value in accordance with livestock needs and performance is the crucial principle of optimal livestock diet and at the same time basic rule for feeding with reduced content of crude protein (CP) (StMELF Bayern, 2003). Employment of CP-low ration is primarily intended to reduce N-content in animal excreta and therefore NH_3 emission potential (Lindermayer, 2002). Beside compliance with animal nutritional requirements, animal diet also must assure higher nutrients ingestion and retention (Urynek *et al.*, 2003; Hélène *et al.*, 2005b; Kirchgeßner, 2004). This section describes specifics of CP-low feeding strategy for sows, fattened pigs, laying hens and broilers. Introduction of CP-restricted diet by cattle is not considered in this work, as there are not enough investigations of different rations effect on livestock productivity and well-being.

Abatement for NH_3 emissions resulted from the introduction of CP-adjusted feeding by different livestock categories is presented in Table 34.

Table 34 Assumptions for **Scenario III**

	Reduction in N excreted in comparison with normal diet, in %
Breeding sows	7.7
Fattened pigs	10-25*
Laying hens	4.1
Broilers	15.8

Notes: * depending of the number of feeding phases, thus 10%-reduction is for one-phase-feeding and 25%-reduction is for three-phases-feeding

Sources: LEL (2009, 2008)

Reduction of NH_3 losses is calculated with the information from LEL (2009) on nutrients content in excreta of animals on standard and CP-low rations. The nutritional values of different dietary ingredients calculated based on their dry matter content, has been taken from DLG (2005) and Kirchgeßner (2004). Prices for amino acids (AAs) and mineral fodder are obtained from German agricultural fodder producer. According to LEL (2009), the employment of CP-reduced feeding results in a comparatively lower protein-N content in animal excreta, i.e., by ca. 4-25% depending on animal type and feeding practise (Table 34).

The objective of **Scenario IIIa** is to determine financial and environmental efficiency of CP-adjusted diets by different types of intensive livestock farms. It has been assumed that the CP-reduced feeding strategy is implemented by 100% of German farms.

In order to understand better functioning principle of the **Scenario III**, the EFEM modelling of fodder supply to animals in BAU has to be explained. In a framework of animal module livestock feeding is presented in a disaggregated way, i.e., as a combination of both ingredients of farm-own and purchased products. In BAU modelling of feeding strategies is based on the idea of farmers' freedom to choose the dietary ingredients of farm-own production. The amount of dietary components for pigs and cattle is adjusted to the animals' nutritional requirements, i.e., to a minimal level of CP, lysine, metabolized energy (ME), and maximal dry matter content. Moreover, combination of ingredients is determined individually for each livestock production activity and animal type within the linear model optimization process. Laying hens and broilers in BAU are fed only with the purchased universal fodder, which amount is restricted through maximal dry matter intake per bird and per annum. Animals nutritional requirements and nutritive values of feeding components are taken from DLG (2005), KIRCHGEßNER (2004), and KTBL (2008a).

In contrast to BAU the *scenario* feeding rations are introduced into EFEM as a composition or dietary ingredients, which partially are of non farm-own production. Setting of maximal quantity for each feeding component allows some modelling flexibility in determination of fodder ingredients' amount based on their costs, nutrients content, and animal requirements. The effect of **Scenario III** is revealed due to the comparison of its results for all relevant animal categories with the respective BAU outcomes.

As various feeding strategies lead to alteration in body organization and energy balance (RAMSAY *et al.*, 2008), individual CP-low diet chosen for each animal type in **Scenario IIIa** had to comply with several criteria named in sections 7.3.1-2.

7.3.1 Pigs

Introduction of CP-low diet by sows is efficient if the feeding ration is adjusted to animals nutritional requirements during two periods of breeding, i.e., lactation and gestation (SPIEKERS *et al.*, 1990). The feeding rations for pregnant sows on two stages of gestation are taken from KIM *et al.* (2009), and for lactating pigs from HÉLÈNE *et al.* (2005b); both diets are shown in Table 35. Feeding ration to implement into EFEM has been calculated as a weight average of dietary compositions with periods for gestation and lactation, covering 77% and 23% of the sows' production cycle, respectively, as weighting factors (KTBL, 2008a). Total nutritional values of animal diets in Table 35 have been computed for the dry matter based nutrients content of fodder plants and other elements (AA, soy bean oil, etc.).

Table 35 Composition of CP-restricted diet for sows

Categories	Units	CP-low diet for gestating sows[1)]		CP-low diet for lactating sows[2)]	Averaged dietary composition
Feeding days		*91*	*164*	*77*	*332*
Corn	%	74.21	74.30	50.25	68.70
Corn starch	%	--	--	7.97	1.85
Soy bean meal, decupled	%	10.08	10.01	1.53	8.06
Wheat	%	--	--	30.00	6.96
Wheat bran	%	--	--	3.00	0.7
Alfalfa meal, 17% CP	%	5.00	5.00	--	3.84
Salt	%	0.35	0.35	0.45	0.37
Dicalcium phosphate	%	2.20	2.20	2.30	2.22
Potassium chloride	%	0.25	0.25	--	0.19
Calcium carbonate	%	0.53	0.5	0.48	0.50
Vegetable oil	%	0.43	0.40	--	0.32
L-Lysine HCl	%	0.53	0.50	0.35	0.3
DL-Methionine	%	--	--	0.02	0.0046
Tryptophan	%	--	--	0.04	0.009
L-Threonine	%	0.18	0.13	0.11	0.14
Molasses	%	5.00	5.00	3.00	4.45
L-Arginine	%	--	0.06	--	0.03
Vitamin- & mineral premix	%	1.50	1.50	0.50	1.27
Sum	%	*100.00*	*100.00*	*100.00*	*100.00*
Nutrient compositions, calculated[3)]					
ME	MJ/kg	14.43	14.43	14.91	14.66
CP	g/kg	152.79	152.51	115.58	144.02
Lysine	g/kg	8.28	8.50	6.68	8.02

Notes: ME -metabolized energy, CP - crude protein

Source: [1)] KIM *et al.* (2009); [2)] HÉLÈNE *et al.* (2005b); [3)] own calculations based on DLG (2005), KIRCHGEßNER (2004) and KTBL (2008a)

The criterion of reduction of N-excreted is fulfilled through lower content of soy bean meal in sows ration, and its partial substitution with CP-low ingredients, like corn (Table 35). However, CP proportions in pigs' diets on different breeding stages must be very well planned, as a higher protein storage gained during gestation and farrowing lead to a low milk production and quality (SINCLAIR *et al.*, 2001; KIM *et al.*, 2009; HÉLÈNE *et al.*, 2005b). Therefore, the diet chosen for pregnant sows has higher protein content than the lactation ration (Table 35).

Limitation of essential AAs is the major consequence of CP-low diet by sows, but addition of AAs into pigs' fodder must be performed with extra caution, since balance of AAs is easy to disturb (KIM *et al.*, 2001). The misbalance can lead to performance reductions by sows and their litter, negatively affect animal health, and cause higher mortality (TOUCHETTE *et al.*, 1998). Due to higher ileal digestibility[33] by gestating pigs (STEIN *et al.*, 1999), dietary ration chosen for sows on this stage content comparatively more AAs (Table 35).

High-energy diets for gestating pigs increase the risk of obesity and high weight loss during lactation (KIM *et al.*, 2009). By lactating sows high-energy diet maintains body fatness and leads to a lower milk fat content, reducing farrows productivity (SINCLAIR *et al.*, 2001). Hence, a maximal ME of 15 MJ has been set for lactating ration (Table 35).

The reaction of sows on dietary modifications depends on pigs' age, weight, breed, and genetic. Here such feature of sow organism as forming of fat reserves during farrowing, that allows maintaining of milk yield and quality, has to be taken into account (HÉLÈNE *et al.*, 2005b; HÉLÈNE *et al.*, 2005a; SINCLAIR *et al.*, 2001).

The main expectation from the introduction of rational feeding by fattened pigs is to favour an optimal meat development and quality, to shorten the fattened period and to assure efficient nutrient uptake. As for sows, fatteners' ration has to be adjusted to nutritional requirements depending on pigs' age and weight (CANH *et al.*, 1998; KIRCHGEßNER, 2004).

Fattened pigs' CP-low diet is primarily results from the exclusion of high protein soy bean meal out of animal ration. However, CP deficiency must be compensated through the higher content of AAs, i.e., methionine, threonine, and tryptophan. This study analyses fatteners' one-phase diet, when the same mixture of the ingredients (universal fodder) is provided during pigs' lifetime, as well as combinations of two, three or even more dietary compositions over fattening period. Levels of protein and mineral fodder are generally reduced simultaneously and gradually for each following feeding phase, which allows meeting of pigs' nutritional requirements and lower N-content in excreta in the best way (KIRCHGEßNER, 2004; SPIEKERS *et al.*, 1990). Feeding strategies for fattened pigs are presented in Table 36. The ration for the incorporation into EFEM is calculated as a weight average of several dietary compositions, with days for each fattening phase as a weighting factor. Total nutritional value is the sum of dry matter based value of all dietary components. Further on averaged feeding ration and its nutritional value is multiplied with the occurrence of feeding options (Table 19, section 5.6).

[33] digestibility of AAs

Table 36 Composition of CP-restricted diet for fattened pigs

Categories	Units	Universal feeding[1)]	2-phase-feeding		Average ration for 2-phase-feeding	3-phase-feeding			Average ration for 3-phase-feeding
Weight range[2)]	*kg*	*35-115*	*20-60*	*60-115*		*25-60*	*60-85*	*85-115*	
Fattening days		*119*	*49*	*70*		*49*	*28*	*42*	
Soy bean meal	%	16.00	21.40	10.90	15.20	14.40	6.30	0.70	7.70
Barley	%	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Wheat	%	30.80	24.70	36.70	31.80	31.60	40.90	46.80	39.20
Vegetable oil	%	1.00	1.20	0.70	0.90	1.00	0.50	0.50	0.70
L-Lysine HCl	%	0.20	0.10	0.20	0.16	0.33	0.39	0.44	0.38
DL-Methionine	%	--	--	--	--	0.03	0.03	0.03	0.03
L-Threonine	%	--	--	--	--	0.07	0.05	0.07	0.07
Mineral fodder	%	2.00	2.50	1.50	1.90	2.50	2.00	1.50	2.00
Sum	*%*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*
Nutrient compositions, calculated[3)]									
ME	MJ/kg	13.01	12.95	13.05	13.01	12.96	12.98	13.03	12.97
CP	g/kg	164	181	148	162	181	153	133	137
Lysine	g/kg	11.09	12.38	9.75	10.83	12.41	10.21	8.71	10.08

Notes: [1)] one feeding ration during total fattening stage; [2)] corresponds to feeding phases; ME - metabolized energy, CP - crude protein

Source: KIRCHGEßNER (2004); [3)] own calculations based on DLG (2005), KIRCHGEßNER (2004), and KTBL (2008a)

The level of ME for each phase in the chosen diets only slightly differs from 13 MJ/kg, as lower dietary ME may cause problems with N-retention. Moreover, rise in the lysine-ME ratio under the sufficient energy intake may considerably improve N-retention. Amount of N in excreta of fattened pigs on 2-phase and 3-phase low-protein diet is lower by 15% and 25%, correspondingly, comparing to respective results from universal feeding (Table 34) (KIRCHGEßNER, 2004; LEL, 2009).

7.3.2 Poultry

Contemporary poultry is mainly kept on the diets with high CP content. The introduction of CP-limited diet by poultry is less financially and environmentally efficient than by pigs mainly due to altering variability within birds flock. However, some poultry producers in agriculture and industry apply CP-low feeding for laying hens and broilers out of ecological concern (MELUZZI *et al.*, 2001; LEL, 2009).

Different feeding schemes, i.e., phase feeding, protein-restricted diets, AAs supplementation, etc., are applicable for laying hens, but for the study analysis the universal ration from MELUZZI *et al.* (2001) has been chosen. This feeding ration is proved as assuring relatively higher egg weight, and better food intake and N utilization (MELUZZI *et al.*, 2001). Its dietary composition is demonstrated in Table 37.

Table 37 Composition of CP-restricted diet for laying hens

Ingredients	**Units**	**Amount**
Yellow maize	%	64.9
Soy bean meal	%	17.8
Wheat gluten	%	2.0
Corn starch	%	3.7
Soy bean oil	%	0.2
Limestone	%	7.6
Dicalcium phosphate	%	2.0
Calcium propionate	%	0.3
Vitamin- mineral premix	%	0.4
L-Lysine HCl	%	0.2
L-Tryptophan	%	0.4
L-Cystine	%	0.2
Sum	*%*	*100*
Nutrient compositions, calculated*		
ME	MJ/kg	11.5
CP	g/kg	155
Lysine	g/kg	10.24

Notes: ME -metabolized energy, CP - crude protein

Source: MELUZZI *et al.* (2001); * own calculations based on DLG (2005), KIRCHGEßNER (2004), and KTBL (2008a)

If energy value of universal diet for laying hens exceeds 11.5 MJ/kg, daily weight gain increases, feed ingestion worsens and feed intake changes. Thus, ME of the chosen diet does not overcome the optimal level (KIRCHGEßNER, 2004).

According to LEL (2009), implementation of CP-low feeding by laying hens results in reduction of excreta-N content by ca. 4.1% (Table 34). However, MELUZZI *et al.* (2001) states that the N reduction in laying hens' manure may reach 11-14% depending on the type of the standard diet to compare with.

Although the possibility to introduce CP-limited diet by broilers is restricted due to birds' short live span of about 4-8 weeks, there is still a chance to implement feeding ration assuring better fodder ingestion and lesser N-excretion (IPEK *et al.*, 2009).

Controversially to pigs, digestion of both protein and fat by broilers results in equal amount of energy, and any limitation in these two nutrients may lead to significant birds' performance and health reduction (KIRCHGEßNER, 2004; MELUZZI *et al.*, 2001; IPEK *et al.*, 2009; ROSEBROUGH *et al.*, 2008; YANG *et al.*, 2009). However, several investigations show that the reduction of ME- and CP-content during the early life stage of broilers (starters) tends to improve nutrients intake and meat quality. That's why the phase feeding strategy with CP-low feeding stage for starters is taken from YANG *et al.* (2009). The experiment carried out by YANG *et al.* (2009) revealed that relatively more efficient utilisation of AAs by birds on CP-restricted diet is a possible reason for lower N-content in broilers' manure, which may be reduced by up to 15.8% (LEL, 2009) (Table 34).

Broilers' CP-restricted diet to incorporate into EFEM is calculated as a weight average of full-protein ration for starting broiler chicks, low-protein feeding, and normal diet for finishers, with feeding days for each stage as weighting factors. Nutritional values of different feeding stages and rations along with average outputs are presented in Table 38.

Table 38 Composition of CP-restricted diet for broilers

Categories	**Units**	**CP-high diet for starters**	**CP-low diet for starters**	**Finishers**	**Average ration**
Number of days		*14*	*6*	*20*	
Maize	%	48.6	60.0	60.2	56.1
Soy bean meal	%	31.3	17.1	22.2	24.6
Maize gluten meal	%	8.5	8.6	8.6	8.6
Wheat bran	%	--	4.2	--	0.6
Soy bean oil	%	7.5	5.8	5.2	6.1
L-lysine HCl	%	--	0.2	0.2	0.1
DL-methionine	%	0.12	0.05	0.01	0.05
Choline chloride	%	0.2	0.2	0.2	0.2
Dicalcium phosphate	%	2.0	2.0	1.5	1.7
Limestone	%	1.3	1.4	1.4	1.3
Salt	%	0.3	0.3	0.3	0.3
Mineral premix	%	0.1	0.1	0.1	0.1
Vitamin premix	%	0.1	0.1	0.1	0.1
Maduramicin	%	0.05	0.01	0.10	0.07
Total	%	*100*	*100*	*100*	*100*
Nutrient compositions, calculated*					
ME	MJ/kg	15.0	14.5	14.6	14.8
CP	g/kg	254	209	226	233
Lysine	g/kg	12.2	9.6	10.9	11.2

Note: ME -metabolized energy, CP - crude protein

Source: YANG *et al.* (2009), * own calculations based on DLG (2005), KIRCHGEßNER (2004) and KTBL (2008a)

7.3.3 Impact of the Scenario with CP-low Feeding (Scenario IIIa)

The **Scenario IIIa** outputs are demonstrated on the example of Weser-Ems, Stuttgart, and Brandenburg. A number of farm animals serves as the selection criterion for study regions shown in Table 39, particularly number of pigs, as this category emits the most NH_3 (23.2%) comparing to poultry (9.2%) (Figure 2, section 2.1.2.1).

Table 39 Number of animals by livestock intensive and mixed farms in Weser-Ems (a) and Lower Saxony, Stuttgart and Baden-Württemberg (b), and Brandenburg (c)

a)

Categories \ Farm type	Units	ILF_Pigs	ILF_Poultry	MF	WE	LS
Number of animals						
Fattened pigs	ap* (×10³)	220	2,081	--	2,301	3,560
Breeding sows	ap (×10³)	388	45	--	433	659
Laying hens	ap (×10³)	--	11,518	--	11,518	13,660
Broilers	ap (×10³)	--	--	22,474	22,474	28,415

b)

Categories \ Farm type	Units	ILF_Pigs	ILF_Poultry	MF	ST	BW
Number of animals						
Fattened pigs	ap* (×10³)	289	--	--	289	653
Breeding sows	ap (×10³)	175	--	--	175	300
Laying hens	ap (×10³)	--	--	1,227	1,227	2,657
Broilers	ap (×10³)	--	456	--	456	848

c)

Categories \ Farm type	Units	ILF_Pigs	ILF_Poultry	MF	BB
Number of animals					
Fattened pigs	ap* (×10³)	11	225	--	236
Breeding sows	ap (×10³)	68	34	--	102
Laying hens	ap (×10³)	--	2,632	--	2,632
Broilers	ap (×10³)	--	3,295	--	3,295

Notes: *ap – animal place; AF – arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; WE – Weser-Ems, ST – Stuttgart, BB – Brandenburg

The *scenario* results for individual farms have been extrapolated to the regional level and shown in Table 40 and Appendixes I, II, and III. The table demonstrates absolute NH_3 emissions, relative values for gross margin per hectare of agricultural land, relative changes of emissions and absolute alteration of gross margin from the BAU outcomes. Average costs of the overall NH_3 emission mitigation serve as an indicator of CP-low diets' financial and abatement efficiency.

Table 40 Average emissions from CP-adjusted fodder by pigs and poultry for different farm types in Weser-Ems and Lower Saxony (a), Stuttgart and Baden-Württemberg (b), and Brandenburg (c)

a)

Farm type / Categories	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS
		Sows							***Fattened pigs***						
Gross margin	EUR/ha	864	1,884	6,551	2,720	2,181	2,190	1,688	864	1,884	6,300	2,782	2,181	2,190	1,688
NH_3 total	kg NH_3-N ($\times10^3$)	974	20,627	5,738	13,944	4,560	45,904	43,259	974	20,594	6,186	14,864	4,560	47,196	45,106
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	--	4.4	-0.2	--	0.7	0.5	--	--	0.4	2.1	--	0.7	0.5
NH_3 organic[1]	%	--	--	-7.1	-6.8	--	-6.9	-5.6	--	--	--	-0.2	--	-0.2	-0.2
NH_3 mineral[2]	%	--	--	-22.8	2.5	--	0.2	0.8	--	--	0.1	0.2	--	0.1	0.2
PM_{10} total	%	--	--	-6.9	--	--	-0.6	-0.3	--	--	--	--	--	--	--
$PM_{2.5}$ total	%	--	--	-7.6	0.1	--	-0.4	-0.2	--	--	--	--	--	--	--
N_2O total	%	--	--	-6.4	-2.1	--	-1.2	-0.4	--	--	--	--	--	-0.3	0.0
CH_4 total	%	--	--	-2.6	--	--	-0.1	-0.1	--	--	-2.9	-10.7	--	-1.3	-0.9
CO_2 total	%	--	--	-3.2	0.5	--	-0.3	-0.1	--	--	--	--	--	--	0.1
GHG total	%	--	--	-4.5	-0.6	--	-0.7	-0.4	--	--	-0.5	-2.1	--	-0.6	-0.3
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	--	-33.4[4]	1.0	--	-9.9[4]	-11.4[4]	--	--	-509[4]	-445[4]	--	-446[4]	-359[4]

Farm type / Categories	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS
		Laying hens							***Broilers***						
Gross margin	EUR/ha	864	1,884	6,275	2,556	2,181	2,132	1,663	864	1,884	6,275	2,725	1,560	2,128	1,658
NH_3 total	kg NH_3-N ($\times10^3$)	974	19,277	6,195	14,376	4,560	45,363	85,352	974	19,292	6,186	14,891	4,229	45,548	84,692
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	--	--	-6.2	--	-2.0	-1.0	--	--	--	--	-28.5	2.1	-1.3
NH_3 organic[1]	%	--	--	--	-3.4	--	-2.4	-0.7	--	--	--	--	-7.3	-0.7	-1.2
NH_3 mineral[2]	%	--	--	--	-3.9	--	-1.2	-0.3	--	--	--	--	-6.8	-0.4	-0.1
PM_{10} total	%	--	--	--	-35.2	--	-19.5	-11.2	--	--	--	--	-13.4	-2.1	-1.3
$PM_{2.5}$ total	%	--	--	--	-51.8	--	-29.6	-17.6	--	--	--	--	-34.7	-5.1	-3.2
N_2O total	%	--	--	--	-0.8	--	-0.2	-0.1	--	--	--	--	-5.2	-0.5	-0.2
CH_4 total	%	--	--	--	--	--	--	0.2	--	--	--	--	1.5	0.1	0.2
CO_2 total	%	--	--	--	6.3	--	3.3	1.8	--	--	--	--	41.5	2.7	1.6
GHG total	%	--	--	--	4.5	--	1.1	0.7	--	--	--	--	14.2	0.8	0.5
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	--	--	72.1	--	72.6	84.0	--	--	--	--	135	136	55.4

b)

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW
		Sows							***Fattened pigs***						
Gross margin	EUR/ha	854	1,736	3,111	1,871	1,381	1,552	1,328	854	1,736	3,083	1,871	1,381	1,549	1,326
NH_3 total	kg NH_3-N ($\times 10^3$)	979	3,652	3,237	82.1	2,722	10,577	14,634	979	3,652	3,471	82.3	2,722	10,961	14,983
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	--	1.7	--	--	0.5	0.4	--	--	0.8	--	--	0.3	0.2
NH_3 organic[1)]	%	--	--	-7.6	--	--	-4.2	-3.4	--	--	-0.1	--	--	-0.1	-1.1
NH_3 mineral[2)]	%	--	--	7.2	--	--	1.4	0.6	--	--	3.9	--	--	0.8	0.4
PM_{10} total	%	--	--	0.2	--	--	0.1	0.1	--	--	--	--	--	--	0.0
$PM_{2.5}$ total	%	--	--	1.0	--	--	0.2	0.1	--	--	--	--	--	--	0.0
N_2O total	%	--	--	-1.8	--	--	-0.5	-0.3	--	--	0.1	--	--	--	0.0
CH_4 total	%	--	--	0.3	--	--	--	0.1	--	--	-7.6	--	--	-0.4	-0.4
CO_2 total	%	--	--	2.7	--	--	0.8	0.8	--	--	0.1	--	--	--	0.0
GHG total	%	--	--	0.3	--	--	0.1	-0.1	--	--	-0.9	--	--	-0.1	-0.1
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	--	-16.6[4)]	--	--	-16.7[4)]	-18.8[4)]	--	--	222	--	--	222	-46.3[4)]
		Laying hens							***Broilers***						
Gross margin	EUR/ha	854	1,736	3,059	1,871	1,345	1,533	1,316	854	1,736	3,057	1,338	1,382	1,542	1,322
NH_3 total	kg NH_3-N ($\times 10^3$)	979	3,920	3,476	82.3	2,701	11,162	14,566	979	3,652	3,476	75.9	2,722	10,903	14,614
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	--	--	--	-2.6	-0.7	-0.5	--	--	--	-28.5	--	-0.1	-0.1
NH_3 organic[1)]	%	--	--	--	--	-0.8	-0.3	-0.5	--	--	--	-8.9	--	0.0	0.0
NH_3 mineral[2)]	%	--	--	--	--	0.4	0.7	0.3	--	--	--	3.8	--	0.7	0.3
PM_{10} total	%	--	--	--	--	-29.8	-7.5	-6.2	--	--	--	-11.1	--	-0.2	-0.1
$PM_{2.5}$ total	%	--	--	--	--	-39.4	-12.0	-9.7	--	--	--	-29.5	--	-0.4	-0.3
N_2O total	%	--	--	--	--	-0.2	0.2	0.1	--	--	--	-1.9	--	0.2	0.1
CH_4 total	%	--	--	--	--	-0.5	-0.2	0.0	--	--	--	--	--	--	0.0
CO_2 total	%	--	--	--	--	6.7	1.4	1.1	--	--	--	29.7	--	0.4	0.1
GHG total	%	--	--	--	--	1.4	0.5	0.4	--	--	--	14.3	--	0.2	0.1
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	--	--	--	230	233	190	--	--	--	149	--	162	382

c)

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB
		Sows						***Fattened pigs***					
Gross margin	EUR ha^{-1}	686	1,089	7,316	25,841	841	927	686	1,089	7,028	25,590	841	924
NH_3 total	kg NH_3-N ($\times 10^3$)	2,627	4,194	814	2,746	10,284	20,665	2,627	4,194	882	2,849	10,284	20,836
		Changes to the reference						**Changes to the reference**					
Gross margin	%	--	--	4.2	2.5	--	0.4	--	--	0.1	1.5	--	0.1
NH_3 organic[1]	%	--	--	-7.6	-3.6	--	-1.1	--	--	--	-0.1	--	0.0
NH_3 mineral[2]	%	--	--	-24.0	-12.2	--	-0.1	--	--	--	0.1	--	0.0
PM_{10} total	%	--	--	-11.6	-0.6	--	-0.2	--	--	-1.0	-0.1	--	0.0
$PM_{2.5}$ total	%	--	--	-12.0	-0.7	--	-0.3	--	--	-0.9	--	--	0.0
N_2O total	%	--	--	-7.1	-4.7	--	-0.2	--	--	--	--	--	--
CH_4 total	%	--	--	-4.8	-0.5	--	-0.1	--	--	-3.6	-7.1	--	-0.3
CO_2 total	%	--	--	-8.5	-2.5	--	-0.6	--	--	-1.1	-0.2	--	-0.1
GHG total	%	--	--	-13.7	-5.3	--	-0.5	--	--	-1.1	-1.5	--	-0.1
		Average abatement costs						**Average abatement costs**					
NH_3 total	EUR/kg NH_3-N	--	--	-36.3[4]	-20.2[4]	--	-26.8[4]	--	--	-195	-383[4]	--	-393[4]

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB
		Laying hens						***Broilers***					
Gross margin	EUR ha^{-1}	686	1,089	7,021	22,740	841	916	686	1,089	7,021	23,824	841	919
NH_3 total	kg NH_3-N ($\times 10^3$)	2,627	4,194	882	2,821	10,284	20,808	2,627	4,194	882	2,803	10,284	20,791
		Changes to the reference						**Changes to the reference**					
Gross margin	%	--	--	--	-9.8	--	-0.8	--	--	--	-5.5	--	-0.4
NH_3 organic[1]	%	--	--	--	-1.1	--	-0.2	--	--	--	-1.7	--	-0.3
NH_3 mineral[2]	%	--	--	--	-1.4	--	0.0	--	--	--	-1.6	--	0.0
PM_{10} total	%	--	--	--	-43.6	--	-5.2	--	--	--	-2.9	--	-0.3
$PM_{2.5}$ total	%	--	--	--	-57.9	--	-8.8	--	--	--	-6.3	--	-1.0
N_2O total	%	--	--	--	-1.1	--	0.0	--	--	--	-1.3	--	0.0
CH_4 total	%	--	--	--	--	--	--	--	--	--	0.1	--	0.0
CO_2 total	%	--	--	--	7.3	--	0.9	--	--	--	3.7	--	0.5
GHG total	%	--	--	--	5.2	--	0.3	--	--	--	2.2	--	0.1
		Average abatement costs						**Average abatement costs**					
NH_3 total	EUR/kg NH_3-N	--	--	--	271	--	273	--	--	--	97.4	--	98.5

Notes: [1] NH_3 from organic manure management; [2] NH_3 from mineral fertilization; [3] no NH_3 emission reduction occurs; [4] NH_3 abatement is bound with profit; AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production, correspondingly, MF – mixed farms; WE – Weser-Ems, ST – Stuttgart, BB – Brandenburg

The implementation of **Scenario IIIa** for sows in study regions reveals overall positive change in gross margin of up to 0.7%. At the farm level, the uppermost boost in a financial gain of ca. 2-4% is detected for intensive livestock farms with the emphasis on pig production. This can be explained by the fact that ca. 90% and 67% of sows in Weser-Ems and Brandenburg, respectively, are concentrated at these farms (Table 39). The gross margin growth rate resulting from feeding of sows with CP-restricted fodder is the uppermost by the regions with the highest livestock density, i.e., Weser-Ems and Lower Saxony 1.4 and 0.9 LU ha^{-1}, correspondingly). Controversially, the financial gain from the introduction of CP-low ration by fattened pigs rises with the uppermost rate of 2% by intensive poultry producing farms comprising 90% and 95% of fattened pigs in Weser-Ems and Brandenburg, correspondingly. In Stuttgart all pig categories are only presented at farms with orientation on pig production; there the gross margin increases due to the scenario implementation for fattened pigs by up to 1% (Table 39 and 40). Boost in gross margin due to the *scenario* implementation by both pigs' categories results from the reduction in animals' ration of soy bean meal, relatively expensive and high in CP ingredient. This allows savings comparatively higher than expenses for compensatory dietary additives (i.e., AAs and mineral fodder), although they constitute ca. 40.7 EUR per sow and 3.4 EUR per fattened pig. However, in this study only one dietary combination has been considered for each animal type. It can be that other CP-limited feeding compositions for pigs appear to be more expensive than normal nutrition, but possibly even more efficient in terms of NH_3 reduction and maintenance of animal productivity and performance. Therefore, more investigations of different CP-limited diets are required.

Controversially to the pigs' case, introduction of CP-low diet for both laying hens and broilers is bound with the gross margin reduction. Moreover, for forage growing and arable regions, like Baden-Württemberg and Brandenburg this decrease for laying hens is higher than for broilers (ca. 0.8% versus 0.4%). Scenario relevant farms are either intensive poultry producing or mixed farms. Feeding of laying hens with CP-adjusted fodder in Weser-Ems results in 9.8% and 28.5% lower financial gain by intensive livestock and mixed farms, respectively. This corresponds with the highest drop off in gross margin at the regional level. Comparatively less considerable is gross margin reduction for Baden-Württemberg and Brandenburg. Although the expenses for dietary additives per laying hen (2.8 EUR ap^{-1}) are much lower than those for pigs, total expenses are about 4 times higher than for sows due to high number of birds in study regions (Table 39). In the case of broilers, the major costs are related to dietary ingredients different from supplementary constituents, e.g., relatively expensive maize and soy bean meal.

Direct effect of **Scenario IIIa** is abatement of NH_3 from animal barn attributed to lower N-content in excreta of animals on CP-adjusted diet. The uppermost NH_3 reduction rate of 7% and 6% occurs due to CP-low feeding of sows in Weser-Ems and Lower Saxony, respectively. The *scenario* introduction for fattened pigs results in NH_3 mitigation effect of 0.1-0.2%, which hardly differs between administrative regions presented in Table 40. However, among federal states, Baden-Württemberg demonstrates the best abatement NH_3 released from bars of fattened pigs on CP-limited ration. Laying hens and broilers fed CP-low fodder cause the highest NH_3 emission reduction for Weser-Ems and Lower Saxony (2.4% and 0.7%, respectively, for laying hens, 0.7% and 1.2%, correspondingly, for broilers) (Table 40).

Alteration in NH_3 losses occurring due to mineral fertilization result from the **Scenario IIIa** implementation, following changes in optimized crop production structure and a lesser N-content in animal excreta. This together with relative value of organic manure defines the direction for development of NH_3 from mineral fertilization. Alterations in crop production structure are minimal; major of them are caused by the pigs' CP-low feeding and nearly no changes arise from the *scenario* introduction for laying hens and broilers. Also the function of manure exchange is important for justification of development of NH_3 emissions from mineral fertilization. Manure exchange ensures farmers the flexibility in finding the most optimal way to maintain soil fertility. Thus, luck of this function in EFEM for Baden-Württemberg results in a boost of NH_3 losses from mineral fertilizers land application (Table 40).

The total NH_3 emission, comprising both NH_3 losses from organic manure management and mineral fertilization, generally declines due to practicing of CP-restricted feeding by pigs and poultry. However, reduction rate for the total NH_3 is lower than diminution of NH_3 losses stemming from manure management, and therefore, maximal and minimal abatement results differ among study regions. Thus, the uppermost decrease for sows and fattened pigs is revealed in Baden-Württemberg (2.3% and 0.6%, respectively), and for laying hens and broilers in Lower Saxony (1.2% and 0.9%, correspondingly). In Brandenburg, total NH_3 emission reduction by both pigs and poultry is less than 1% (Appendixes I, II, and III).

The CP-low diet by animals is only indirectly cause any alterations in PM emissions and can primarily be explained with the changes of PM losses for the upstream production sector and namely production of AAs and other additives for the CP-low dietary composition. Mainly PM losses decrease with relatively high rate by *scenario* relevant intensive livestock and mixed farms, i.e., 0.2-29.8% for PM_{10} and 1.0-39.4% for $PM_{2.5}$ in Stuttgart, 0.0-35.2% for

PM_{10} and 0.0-51.8% for $PM_{2.5}$ in Weser-Ems, and 0.6-43.6% for PM_{10} and 0.7-57.9% for $PM_{2.5}$ in Brandenburg (Table 40).

Total GHG losses in Lower Saxony, Baden-Württemberg, and Brandenburg reduce only due to the **Scenario IIIa** implementation for pigs by negligible rates. Feeding of poultry with CP-adjusted fodder results in the increase of total GHG emissions by less than 1% in all study regions. The contribution of individual GHGs to the total emissions does not follow a clear trend and depends on farm types and animal categories (Table 40).

The most efficient NH_3 emission abatement is detected for livestock intensive Weser-Ems and Lower Saxony, i.e., 72.6 and 84.0 EUR/kg NH_3-N, correspondingly, for laying hens and 136 and 55.4 EUR/kg NH_3-N, respectively, for broilers. Due to minimal NH_3 emission abatement and much higher costs of CP-adjusted dietary compositions, introduction of CP-low feeding practise appears to be the most expensive for poultry in forage growing Baden-Württemberg and arable Brandenburg, i.e., 190 and 273 EUR/kg NH_3-N, correspondingly, for laying hens and 55.4 and 382 EUR/kg NH_3-N, respectively, for broilers. Profit from the scenario implementation for pigs on the background of relatively low total NH_3 reduction speaks for financial gain due to the NH_3 abatement. However, this would make any economic sense only when reduced and not because of the gross margin reduction, but rather due to a higher NH_3 mitigation.

7.3.4 Different CP-low Feeding Strategies for Fattened Pigs (Scenario IIIb)

The results of the CP-low diet introduction for fattened pigs differ depending on the number of feeding stages and the occurrence of different feeding strategies, i.e., 1-phase, 2-phase, 3-phase, and multi-phase feeding. In the framework of this section and due to the implementation of **Scenario IIIb** it has to be revealed, how modelling outcomes change due to the employment of each above-mentioned feeding strategy for fattened pigs at 100% of relevant German farms. The *scenario* outputs have been compared to the results of BAU and presented together with results of **Scenario IIIa** for fattened pigs. The occurrence of feeding practises is discussed in section 5.6, and presented in Table 19. The **Scenario IIIb** results are introduced in Figure 16 for Weser-Ems, Stuttgart, and Brandenburg.

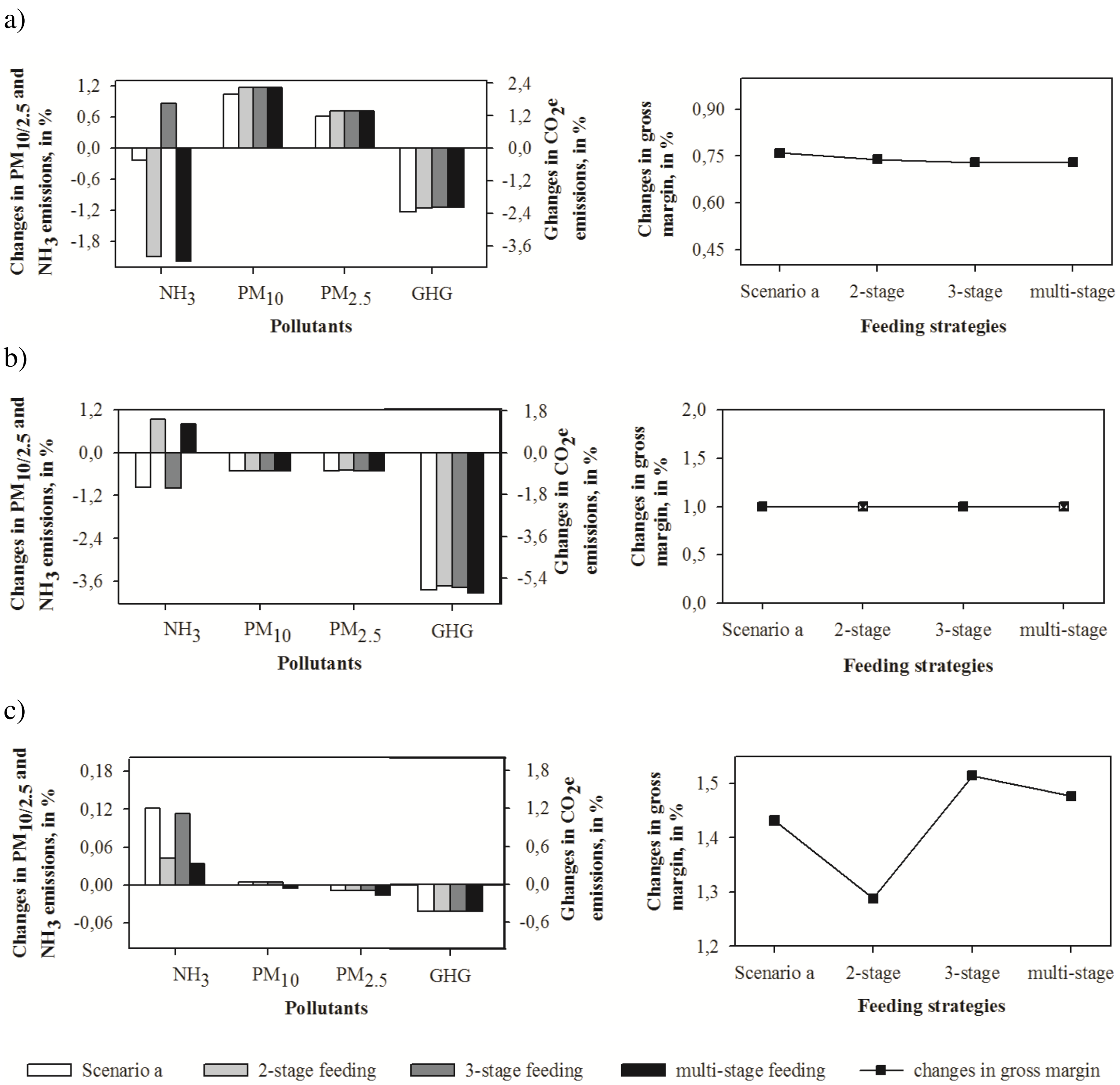


Figure 16 Relative changes in NH_3, PM, and GHG emissions and gross margin (in %) resulting from **Scenarios IIIa** and **b** for Weser-Ems (a), Stuttgart (b), and Brandenburg (c).

Application of different CP-limited feeding strategies for fattened pigs is bound with financial gain increase comparing to the BAU outputs, and can be explained by a gradual exclusion of soy bean meal from animals diets (Table 36). Changes in optimal solution imply deterioration of gross margin growth rate. Thus, the introduction of CP-adjusted ration in two stages assures lower profit in Brandenburg comparing to financial outcomes of 1-phase feeding (**Scenario IIIa** results). Meanwhile, in Weser-Ems the implementation of 3-stage feeding is comparatively more costly than feeding of fatteners of the same region in two stages. Following the same criterion, the *scenario* implementation is the most profitable for 3-stage pig feeding in Brandenburg. However, gross margin growth rates hardly differ for various feeding strategies in Weser-Ems and Stuttgart reaching maximal 0.8% and 1%, respectively.

Figure 16 demonstrates negligible changes in NH_3 emissions resulting from the *scenario* implementation in Brandenburg, but even here the total NH_3 losses boost up slightly comparing to the BAU outcomes. However, in Weser-Ems, the study region with a relatively higher livestock density of 1.4 LU ha^{-1}, the 2-stage and multi-stage feeding of fattened pigs leads to the reduction of NH_3 losses, i.e., by nearly 2.0%. This can be explained by the different cumulative results of the NH_3 emitted from such sources as manure storage and land application for each particular study region.

Similar to **Scenario IIIa** emissions of PM and GHG resulting from the implementation of **Scenario IIIb** only slightly alter from BAU. Nevertheless, PM losses increase by ca. 1.5% for Weser-Ems and decline by nearly 0.5% for Stuttgart in average for all feeding strategies. This difference for both regions with a high livestock density can be justified by the fact that the adjustments of the optimal solution to the scenario conditions are individual for each region. GHG emissions decline in all study regions, but with different ratios: from 0.03% in Brandenburg to ca. 4% in Stuttgart. There are minimal changes for PM and GHG losses in Brandenburg.

Relatively high average abatement costs results from the introduction of multi-stage CP-low diet for fattened pigs in Weser-Ems (ca. 31 EUR/kg NH_3-N) and from feeding of animals with CP-adjusted fodder in three stages in Stuttgart and Brandenburg (322 and 129 EUR/kg NH_3-N, respectively). Due to a higher financial gain and slight reduction of NH_3 losses, strategies with 2- and 3-phase feeding in Weser-Ems, more than one feeding phase in Stuttgart and multi-phase feeing in Brandenburg result in profit for the reduction of NH_3 emissions by 1 kg (Table 40).

Highlighting the outputs of **Scenarios IIIa** and **b**, it has to be mentioned that results of CP-adjusted diet introduction vary depending on the animal category, number of animals, farm type, and region. Although CP-low feeding of pigs is related to the positive financial results, the total NH_3 abatement hardly exceeds 2%. As it was mentioned in the section 7.3.3, such profit is welcome, when it does reflects both considerable financial and ecological efficiency, and as ecological efficiency is preferential for this study, the emission abatement must be much higher and resulting average profit much lower. Hence, more CP-low dietary compositions and phase feeding strategies have to be investigated for a more ecologically efficient CP-low feeding strategy.

7.4 Abatement of NH_3 Emission: Environmentally Friendly Techniques for Liquid Manure Storage and Land Application

The idea that livestock excreta are residues of animal production over times was substituted with the agricultural producers' interest to the organic manure as a valuable mean to maintain soil nutrients content. Moreover, soon it became clear that there are more manure produced than it can be applied onto the land and that the excess of organic fertilizers not stored and spread properly negatively affects animal and human health, local ecosystems, and climate due to emissions of NH_3 and GHG gases (RIEß *et al.*, 1990). Nowadays, when the problems of environmental protection and health safety are of a higher priority at the local and global level, more measures are applied in manure management to minimize a negative ecological effect. Following sections describe different options for environmentally friendly handling of organic manure leading to NH_3 abatement.

7.4.1 Introduction of the Manure Storage Cover (Scenario IV)

Minimization of NH_3 losses from storage of livestock manure is the important measure allowing preservation of manure N-content and therefore increasing amount of N potentially available for plants. The main **Scenario IV** assumption is that several types of covers for storage of liquid organic manure are installed by 100% of German farms. In the *scenario* only storage of untreated slurry is analysed; formation of natural crust and keeping of liquid manure underneath slatted floor are not taken into account, as the first measure is mainly possible by cattle and hardly controllable, and the second one is generally applied only during limited time period. The *scenario* objective is to analyse environmental and financial efficiency of different cover types installed by manure storage: tent roof, floating film, granulate, Hexa-cover, concrete cover, and vehicle access concrete cover.

Annual prices for manure storage covers are calculated based on the data for investment requirements, service life, maintenance, and interest for manure storage covers and for storage capacities with diameters of 10, 15, 18.5, 25 and 33 meters. The data for the price calculation is taken from KTBL (2002) and the results are calibrated with costs for manure storage confinements with the diameter 15 meters for the year 2003 from KTBL (2005). It is assumed that the prices alter from 2003 to 2015 with the factor of 1.97 (equivalent to diesel price change), calculated based on the information provided in OFFERMANN *et al.* (2009). The capacities vary from federal state to federal state and from farm to farm depending on the amount of manure excreted during 6 months (minimal excreta amount, which the size of manure storage tanks must be adjusted to (section 3.2)). The prices for the manure storage covers along with their NH_3 abatement efficiency are presented in Table 41. Depending on the amount of manure to store and thereafter, dimensions of manure storage confinement, their prices in the table vary from 1 to 2 in Baden-Württemberg, from 2 to 3 in Lower Saxony and from 4 to 5 in Brandenburg.

Table 41 Annual prices for different manure storage covers in 2003, in EUR year^{-1}

Storage cover type	**Abatement efficiency, %**	**Annual prices for storage capacities*, EUR year^{-1}**				
		1	**2**	**3**	**4**	**5**
Granulate	85	185	313	568	1.125	2.274
Hexa-Cover	94	314	400	571	1.005	1.714
Floating film	85	540	662	1.046	1.763	2.962
Tent roof	90	537	663	1.114	2.042	3.846
Concrete cover	90	319	736	1.570	3.674	8.838
Vehicle-access concrete cover	90	336**	775**	--	--	--

Notes: *the information on storage capacities has been presented in following order: volume/height/diameter/width**;** **own calculations based on the data from DÖHLER *et al.* (2002); 1 - 250m^3/4m/10m/6.25m; 2 - 500m^3/4m/15m/8.3m; 3 – 1.000m^3/4m/18.5m/13.51m; 4 – 2.200m^3/4m/25m/22m; 5 – 5.000m^3/4m/33m/37.9m.

Sources: KTBL (2002, 2005)

Results of **Scenario IV** in comparison to BAU outputs are presented in Table 42. For the demonstration of the *scenario* outputs, livestock intensive administrative regions, i.e., Weser-Ems and Stuttgart, have been selected.

Table 42 Results from application of particular type of manure storage covers by different farm categories in Weser-Ems (a), Stuttgart (b), and Brandenburg (c)

a)

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS
		Granulate							***Floating film***						
Gross margin	EUR/ha	864	1,878	6,213	2,714	2,177	2,165	1,675	864	1,865	6,191	2,703	2,170	2,155	1,667
NH_3 total	kg NH_3-N ($\times 10^3$)	974	20,998	5,371	13,432	4,443	45,219	80,769	974	19.225	5,318	13,432	4,412	43,361	78,559
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	-0.3	-1.0	-0.5	-0.2	-0.5	-0.3	--	-1.1	-1.4	-0.9	-0.5	-0.9	-0.8
NH_3 organic[1)]	%	--	-12.0	-13.8	-9.3	-2.8	-10.6	-9.2	--	-12..0	-13.6	-9.3	-2.8	-10.5	-10.4
NH_3 mineral[2)]	%	--	-10.4	17.1	-19.4	-3.8	-7.5	-2.6	--	-3.8	17.1	-19.4	-3.8	-6.5	-2.2
PM_{10} total	%	--	--	0.3	0.0	--	0.0	0.0	--	--	0.3	0.0	--	0.0	0.0
$PM_{2.5}$ total	%	--	-0.1	1.6	-0.1	--	0.0	0.0	--	-0.1	1.6	-0.1	--	0.0	0.0
N_2O total	%	--	-0.2	8.8	-3.0	0.1	0.0	0.1	--	1.2	8.8	-3.0	0.1	0.5	0.4
CH_4 total	%	--	-0.1	--	--	0.1	-0.1	-0.2	--	--	--	--	0.1	0.0	0.0
CO_2 total	%	--	-0.4	2.6	-0.5	-0.5	0.1	0.0	--	-0.4	2.6	-0.5	-0.5	0.1	0.1
GHG total	%	--	-0.1	3.7	-1.0	0.0	0.0	0.0	--	0.3	3.7	-1.0	--	0.2	0.2
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	1.0	4.1	2.0	1.8	1.8	2.0	--	3.1	5.6	3.7	5.6	3.8	4.2

		Tent roof							***Concrete cover***						
Gross margin	EUR/ha	864	1,864	6,182	2,701	2,169	2,154	1,667	864	1,861	6,196	2,710	2,167	2,155	1,668
NH_3 total	kg NH_3-N ($\times 10^3$)	974	19,044	5,236	13,292	4,404	42,949	78,510	974	19982	5,233	13,292	4,404	43,885	80,027
		Changes to the reference							**Changes to the reference**						
Gross margin	%	-	-1.1	-1.5	-1.0	-0.5	-1.0	-0.8	--	-1.2	-1.3	-0.7	-0.6	-0.9	-0.7
NH_3 organic[1)]	%	--	-12.9	-14.9	-10.2	-3.1	-11.4	-10.4	--	-8.4	-15.0	-10.2	-3.1	-9.3	-8.4
NH_3 mineral[2)]	%	--	-5.1	18.8	-21.3	-3.0	-7.2	-2.6	--	-11.1	18.8	-21.3	-3.0	-8.1	-2.7
PM_{10} total	%	--	0.1	0.4	0.0	--	0.0	0.0	--	0.0	0.4	0.0	--	0.0	0.0
$PM_{2.5}$ total	%	--	0.0	1.8	-0.1	--	0.1	0.0	--	-0.1	1.8	-0.1	--	0.0	0.0
N_2O total	%	--	1.1	9.2	-3.6	0.4	0.4	0.2	--	--	10.2	-3.6	0.4	0.1	0.2
CH_4 total	%	--	-0.1	--	--	-0.9	-0.1	0.0	--	-0.1	0.2	--	-0.9	-0.1	-0.1
CO_2 total	%	--	-0.6	2.9	-0.5	0.4	0.2	0.1	--	-0.5	2.9	-0.5	0.4	0.2	0.1
GHG total	%	--	0.2	4.0	-1.2	-0.1	0.1	0.1	--	0.1	4.3	-1.2	-0.1	0.0	0.1
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	2.9	5.6	3.6	5.6	3.6	4.3	--	5.1	4.8	2.4	6.7	4.1	4.8

Categories / Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS
		Hexa-Cover							***Vehicle access concrete cover***						
Gross margin	EUR/ha	864	1,874	6,202	2,709	2,177	2,161	1,672	864	1,859	6,200	2,707	2,168	2,154	1,667
NH_3 total	kg NH_3-N ($\times 10^3$)	974	20,216	5,314	13,432	4,412	44,348	80,414	974	18,763	5,288	13,292	4,407	42,723	77,855
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	-0.5	-1.2	-0.7	-0.2	-0.6	-0.5	--	-1.3	-1.3	-0.7	-0.6	-1.0	-0.8
NH_3 organic[1)]	%	--	-7.4	-13.6	-9.3	-2.8	-8.4	-8.0	--	-15.5	-15.2	-10.2	-3.1	-12.6	-12.1
NH_3 mineral[2)]	%	--	-3.0	17.1	-19.4	-3.8	-6.4	-2.3	--	-5.1	18.8	-21.3	-3.0	-7.2	-2.6
PM_{10} total	%	--	--	0.3	0.0	--	0.0	0.0	--	0.1	0.4	0.0	--	0.0	0.2
$PM_{2.5}$ total	%	--	--	1.6	-0.1	--	0.0	0.0	--	0.0	1.8	-0.1	--	0.1	0.0
N_2O total	%	--	1.5	8.8	-3.0	0.1	0.6	0.3	--	1.0	9.2	-3.6	0.4	0.4	0.2
CH_4 total	%	--	--	--	--	0.2	--	0.1	--	-0.1	--	--	-0.9	-0.1	-0.2
CO_2 total	%	--	-0.5	2.6	-0.5	-0.5	0.1	0.1	--	-0.6	2.9	-0.5	0.4	0.2	0.0
GHG total	%	--	0.3	3.7	-1.0	--	0.2	0.1	--	0.2	3.9	-1.2	-0.1	0.1	0.0
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	2.5	4.9	2.8	1.9	3.1	3.3	--	3.1	4.8	2.8	6.8	3.3	3.6

b)

Categories / Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW
		Granulate							***Floating film***						
Gross margin	EUR/ha	854	1,731	3,058	1,867	1,378	1,542	1,320	854	1,717	3,044	1,847	1,364	1,533	1,311
NH_3 total	kg NH_3-N ($\times 10^3$)	979	3,680	3,030	79.2	2,466	10,235	28,850	979	3,683	3,030	79.2	2,466	10,238	28,671
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	-0.3	0.0	-0.2	-0.2	-0.1	-0.3	--	-1.1	-0.5	-1.3	-1.2	-0.7	-0.9
NH_3 organic[1)]	%	--	-5.4	-13.0	-3.9	-7.4	-8.4	-7.0	--	-5.4	-13.0	-3.9	-7.4	-8.4	-7.7
NH_3 mineral[2)]	%	--	-8.0	-5.8	-1.6	-4.8	-2.0	-1.2	--	-5.0	-5.8	-1.6	-4.8	-1.8	-1.1
PM_{10} total	%	--	-0.8	-0.1	--	0.0	-0.1	0.0	--	-0.1	-0.1	--	0.0	0.0	0.0
$PM_{2.5}$ total	%	--	-2.0	-0.3	--	-0.1	-0.3	-0.1	--	-0.2	-0.3	--	-0.1	-0.1	-0.1
N_2O total	%	--	0.2	1.2	-0.2	-0.2	0.3	0.4	--	0.8	1.2	-0.2	-0.2	0.4	0.5
CH_4 total	%	--	0.2	--	--	0.1	0.2	0.0	--	--	--	--	-0.1	-0.1	0.0
CO_2 total	%	--	-2.7	-1.0	-0.3	-0.6	-0.7	-0.4	--	-0.6	-1.0	-0.3	-0.6	-0.5	-0.3
GHG total	%	--	0.0	0.4	-0.2	-0.1	0.1	0.1	--	0.2	0.4	-0.2	-0.2	0.1	0.1
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	2.5	0.2	2.2	1.8	1.2	2.0	--	8.9	2.3	13.6	11.8	6.2	7.7

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW
		Tent roof							***Concrete cover***						
Gross margin	EUR/ha	854	1,717	3,044	1,849	1,364	1,532	1,311	854	1,713	3,053	1,862	1,373	1,536	1,314
NH_3 total	kg NH_3-N ($\times 10^3$)	979	3,437	2,989	78.7	2,433	9,917	28,698	979	3,437	2,989	78.7	2,433	9,916	28,695
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	-1.1	-0.5	-1.2	-1.2	-0.8	-0.9	--	-1.3	-0.2	-0.5	-0.6	-0.5	-0.7
NH_3 organic[1)]	%	--	-11.8	-14.3	-4.6	-8.6	-11.8	-7.6	--	-11.8	-14.3	-4.6	-8.6	-11.8	-7.6
NH_3 mineral[2)]	%	--	-5.9	-6.4	-1.8	-5.6	-2.0	-1.2	--	-5.9	-6.4	-1.8	-5.6	-2.0	-1.3
PM_{10} total	%	--	-0.1	-0.1	--	0.0	0.0	0.0	--	-0.1	-0.1	--	0.0	0.0	0.0
$PM_{2.5}$ total	%	--	-0.2	-0.4	--	-0.1	-0.1	-0.1	--	-0.2	-0.3	--	-0.1	-0.1	-0.1
N_2O total	%	--	0.6	1.0	-0.3	-0.3	0.3	0.4	--	0.6	1.0	-0.3	-0.3	0.3	0.5
CH_4 total	%	--	--	--	--	0.4	0.2	0.0	--	--	--	18.4	0.0	0.1	0.0
CO_2 total	%	--	-0.7	-1.1	-0.4	-0.7	-0.5	-0.4	--	-0.7	-1.1	-0.4	-0.7	-0.5	-0.4
GHG total	%	--	0.1	0.3	-0.2	0.0	0.1	0.1	--	0.1	0.3	4.6	-0.2	0.1	0.1
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	4.2	2.3	11.3	10.0	4.6	7.8	--	4.7	0.8	5.0	4.6	3.1	6.6
		Hexa-Cover							***Vehicle access concrete cover***						
Gross margin	EUR/ha	854	1,727	3,053	1,860	1,373	1,539	1,318	854	1,712	3,053	1,858	1,373	1,535	1,312
NH_3 total	kg NH_3-N ($\times 10^3$)	979	3,683	3,030	79.2	2,466	10,238	29,185	979	3,730	2,989	78.7	2,433	10,210	28,995
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	-0.5	-0.2	-0.6	-0.6	-0.3	-0.4	--	-1.4	-0.2	-0.7	-0.6	-0.6	-0.8
NH_3 organic[1)]	%	--	-5.4	-13.0	-3.9	-7.4	-8.4	-5.8	--	-4.1	-14.3	-4.6	-8.6	-8.7	-6.5
NH_3 mineral[2)]	%	--	-5.0	-5.8	-1.6	-4.8	-1.8	-1.1	--	-5.9	-6.4	-1.8	-5.6	-2.0	-1.2
PM_{10} total	%	--	-0.1	-0.1	--	0.0	0.0	0.0	--	-0.1	-0.1	--	0.0	0.0	0.0
$PM_{2.5}$ total	%	--	-0.2	-0.3	--	-0.1	-0.1	-0.1	--	-0.2	-0.4	--	-0.1	-0.1	-0.1
N_2O total	%	--	0.8	1.2	-0.2	-0.2	0.4	0.5	--	-0.8	1.0	-0.3	-0.3	0.3	0.4
CH_4 total	%	--	--	--	--	-0.1	-0.1	0.0	--	--	--	--	-0.1	-0.1	0.0
CO_2 total	%	--	-0.6	-1.0	-0.3	-0.6	-0.5	-0.3	--	-0.9	-1.1	-0.4	-0.7	-0.6	-0.4
GHG total	%	--	0.2	0.4	-0.2	-0.2	0.1	0.1	--	0.2	0.3	-0.2	-0.2	0.0	0.1
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	4.0	0.8	6.0	5.5	2.7	4.8	--	14.1	1.0	6.1	5.2	4.6	8.3

c)

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB
		Granulate						***Floating film***					
Gross margin	EUR/ha	686	1,089	6,958	24,934	839	920	686	1,089	6,951	24,934	838	918
NH_3 total	kg NH_3-N ($\times 10^3$)	2,627	3,661	747	2,637	9,528	19,200	2,627	3,661	747	2,658	9,528	19,221
		Changes to the reference						**Changes to the reference**					
Gross margin	%	--	--	-0.9	-1.1	-0.2	-0.3	--	--	-1.0	-1.1	-0.4	-0.5
NH_3 organic[1)]	%	--	--	-15.6	-7.8	-6.2	-5.6	--	--	-15.6	-7.1	-6.2	-5.4
NH_3 mineral[2)]	%	--	--	19.0	8.2	-0.5	-0.2	--	--	19.0	8.2	-0.5	-0.2
PM_{10} total	%	--	--	0.5	0.1	0.0	0.0	--	--	0.5	0.1	0.0	0.0
$PM_{2.5}$ total	%	--	--	1.7	0.3	-0.1	0.0	--	--	1.7	0.3	-0.1	0.0
N_2O total	%	--	--	9.6	6.1	--	0.4	--	--	9.6	6.0	0.0	0.4
CH_4 total	%	--	--	--	--	--	-0.2	--	--	--	--	--	--
CO_2 total	%	--	--	2.5	1.6	-0.2	0.2	--	--	2.5	1.6	-0.2	0.2
GHG total	%	--	--	4.1	2.2	0.0	0.2	--	--	4.1	2.2	-0.1	0.2
		Average abatement costs						**Average abatement costs**					
NH_3 total	EUR/kg NH_3-N	--	--	3.9	4.4	2.7	4.9	--	--	4.5	5.1	5.3	7.5

		Tent roof						***Concrete cover***					
Gross margin	EUR/ha	686	1,089	6,937	24,833	837	917	686	1,089	6,916	24,768	833	911
NH_3 total	kg NH_3-N ($\times 10^3$)	2,627	3,661	735	2,618	9,451	19,091	2,627	3,661	735	2,618	9,451	19,091
		Changes to the reference						**Changes to the reference**					
Gross margin	%	--	--	-1.2	-1.5	-0.5	-0.6	--	--	-1.5	-1.7	-1.0	-1.3
NH_3 organic[1)]	%	--	--	-17.1	-8.5	-7.2	-6.3	--	--	-17.1	-8.5	-7.2	-6.3
NH_3 mineral[2)]	%	--	--	20.9	9.0	-0.6	-0.2	--	--	20.9	9.0	-0.6	-0.2
PM_{10} total	%	--	--	0.5	0.1	0.0	0.0	--	--	0.5	0.1	0.0	0.0
$PM_{2.5}$ total	%	--	--	1.9	0.4	-0.1	0.1	--	--	1.9	0.4	-0.1	0.1
N_2O total	%	--	--	10.0	6.3	-0.1	0.4	--	--	10.1	6.4	-0.1	0.4
CH_4 total	%	--	--	--	--	--	--	--	--	--	--	--	--
CO_2 total	%	--	--	2.7	1.8	-0.3	0.2	--	--	2.7	1.8	-0.3	0.2
GHG total	%	--	--	4.3	2.3	-0.1	0.2	--	--	4.3	2.4	-0.1	0.2
		Average abatement costs						**Average abatement costs**					
NH_3 total	EUR/kg NH_3-N	--	--	4.7	5.4	5.4	8.2	--	--	6.0	6.1	11.2	16.9

Farm type / Categories	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB
				Hexa-Cover			
Gross margin	EUR/ha	686	1,089	6,962	24,919	840	914
NH_3 total	kg NH_3-N (×10^3)	2,627	3,661	747	2,637	9,528	19,200
				Changes to the reference			
Gross margin	%	--	--	-0.9	-1.1	-0.2	-0.3
NH_3 organic[1)]	%	--	--	-15.6	-7.8	-6.2	-5.6
NH_3 mineral[2)]	%	--	--	19.0	8.2	-0.5	-0.2
PM_{10} total	%	--	--	0.5	0.1	0.0	0.0
$PM_{2.5}$ total	%	--	--	1.7	0.3	-0.1	0.0
N_2O total	%	--	--	9.6	6.0	0.0	0.4
CH_4 total	%	--	--	--	--	--	--
CO_2 total	%	--	--	2.5	1.6	-0.2	0.2
GHG total	%	--	--	4.1	2.2	-0.1	0.2
				Average abatement costs			
NH_3 total	EUR/kg NH_3-N	--	--	4.0	4.5	2.0	4.0

Notes: [1)] NH_3 losses from manure management; [2)] NH_3 losses from application of mineral fertilizers; [3)] no reduction of NH_3 emissions occurs; AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; HA – Hannover, LS – Lower Saxony, FR – Freiburg, BW – Baden-Württemberg, BB – Brandenburg.

The discrepancy in coverage prices and sizes of storage capacities determine changes of the scenario's financial effect. According to Table 42, the employment of granulate for covering of slurry storage results in the lowest gross margin reduction in all study regions and their administrative units, varying from -0.1% in Stuttgart to 0.5% in Weser-Ems. Financial gain decreases with moderate rates of 0.3-0.6% due to the installation of Hexa-Cover. The uppermost decrease of gross margin follows the introduction of tent roof by slurry tanks in Weser-Ems and Stuttgart (nearly 1%) and Brandenburg (about 0.8%).The same expensive is the employment of floating film and vehicle-access concrete cover in the study regions (Table 42, Appendixes I, II, and III). At the farm level, the strongest negative financial effect of **Scenario IV** is detected for intensive pig farms in Weser-Ems (1.0-1.5%) and forage growing in Stuttgart (0.3-1.4%). The gross margin reduction rate in Brandenburg is the highest for intensive livestock farms with the orientation of poultry production, i.e., 1.1-1.7% depending on the cover type. The scenario does not reveal any changes for the forage growing farms in Brandenburg, as in BAU it is assumed that livestock there is housed on deep litter (section 5.6), and thus, abatement measures are not applicable to dung and leachate storage.

Covers' NH_3 reduction potentials in Table 41 are adjusted due the modelling procedure and, particularly, *scenario* assumptions. Thus, the highest abatement of total NH_3 emissions results from the installation of vehicle-access concrete cover in Lower Saxony (ca. 11%), floating film in Baden-Württemberg (about 7%), and tent roof and concrete cover in Brandenburg (nearly 5%). Changes of total NH_3 released due to the *scenario* implementation depend on alteration of NH_3 emissions from manure management and mineral fertilization. The uppermost mitigation of NH_3 from manure management results from the employment of tent roof and concrete cover in Stuttgart (by about 12%) and floating film in Baden-Württemberg (ca. 8%). However, the most efficient emission reduction of 13% follows the slurry storage covering with vehicle-access concrete cover in Lower Saxony and Weser-Ems. Abatement of NH_3 from manure management in Brandenburg is comparatively low, with the highest rate of 7% due to tent roof and concrete cover installation (Table 42, Appendixes I, II, and III).

Emissions of NH_3 from mineral fertilization decrease due to the *scenario* implementation by up to 3% in Lower Saxony, over 1% in Baden-Württemberg and by negligible rate in Brandenburg (Table 42, Appendixes I, II, and III). This reduction follows the preservation of stored slurry NH_4-content and thus higher substitution value of organic N in excreta.

Changes of total PM and GHG losses are negligible and mainly results from slight alterations of optimal crop production structure occurring due to the *scenario* assumptions (Table 42).

Introduction of granulate for covering of manure storage tanks is followed by the cheapest NH_3 abatement in all regions, i.e., up to 2.0 EUR/kg NH_3-N in Lower Saxony and Weser-Ems, and 2.1 and 1.2 EUR/kg NH_3-N in Baden-Württemberg and Stuttgart, respectively. More affordable NH_3 mitigation of 4.0 EUR/kg NH_3-N in Brandenburg is expected from the use of Hexa-cover. Reduction of NH_3 emissions is the most expensive for concrete cover installation in Weser-Ems and Lower Saxony (up to 5.0 EUR/kg NH_3-N) and in Brandenburg (ca. 17.0 EUR/kg NH_3-N) and for veihicle-acess concrete cover and floating film in Baden-Württemberg (over 8.0 EUR/kg NH_3-N). At the farm level, the cheapest NH_3 reduction is detected for pigs producing intensive livestock farms in Stuttgart and Brandenburg (up to 2.3 and 6.0 EUR/kg NH_3-N, correspondingly) and forage growing farms in Weser-Ems (up to 5.1 EUR/kg NH_3-N).

Among the covering materials with relatively low NH_3 reduction potential granulate leads to the cheapest NH_3 abatement due to its lower costs. However, the employment of Hexa-cover is the most efficient and affordable in Brandenburg, with large storage confinements. The higher livestock density and land endowments, the cheaper the scenario outputs, as in Lower Saxony and Baden-Württemberg and other way round, as in Brandenburg.

7.4.2 Manure Land Application (Scenario V)

There is much higher NH_3 emissions released due to manure land application comparing to losses from animal barn and manure storage (section 5.2.5, Table 10). The employment of environmentally friendly slurry spreading techniques results in considerably high NH_3 abatement. However, these abatement options must come up with state of the art and have to be carried out at efficient management of time and manure amount to improve the nutrients use by crops and prevents their washing out and hence contamination of the groundwater.

In **Scenario V** different NH_3 abating manure application techniques like trailing shoe, slurry tooth extirpator and shallow injector are checked for their ecological and financial efficiency. For this sake, it is assumed that each technique is applied by 100% of German farms, and slurry tooth extirpator can only be employed ones per year, namely after crop harvesting, and only for unsown arable land. Financial aid for environmentally friendly manure land application is not considered (section 5.6, Table 19).

Costs, NH_3 emission abatement potentials for different techniques, and types of land management, i.e., arable farming and grassland, are presented in Table 43. The information stems from KTBL (2002, 2004, 2005). Considering that operations of manure land application with trailing shoe, slurry tooth extirpator and shallow injection are conducted through machinery rings and contractors, the computed costs for manure spreading are calibrated with contractor's prices 2003 and projected for the year 2015 with the factor of 1.97 (equivalent to the price change for diesel) taken from OFFERMANN *et al.* (2009).

Table 43 Costs of manure land application techniques (in EUR m^{-3}) and their NH_3 reduction potential (in %)

Federal states	**LS**		**BW**		**BB**		**NH_3 abatement, %***	
	2003	**2015**	**2003**	**2015**	**2003**	**2015**	**Arable land**	**Grassland**
Broadband	2.35	3.48	2.68	3.98	1.92	2.85	--	--
Trailing shoe	4.00	5.94	4.50	6.68	3.50	5.20	60	40-60
Slurry tooth extirpator	4.50	6.68	5.00	7.43	4.00	5.94	80	--
Shallow injection	4.25	6.31	4.75	7.05	3.75	5.57	--	60-80
Solid manure spreading	3.15	4.28	3.48	4.78	2.82	3.75	--	--

Note: LS – Lower Saxony, BW – Baden-Württemberg, BB – Brandenburg; * the abatement potential depends on the manure and animal type (section 5.2.5)

Sources: DÖHLER (2002) and KTBL (2002, 2004)

Results of **Scenario V** are demonstrated for the administrative regions with relatively high livestock number and therefore more organic manure produced. The *scenario* outputs for five farm categories and for study regions are shown in Table 44 and in Appendixes I, II, and III.

Table 44 Results from employment of particular type of manure land application techniques by different farm categories in Weser-Ems (a), Stuttgart (b), and Brandenburg (c)

a)

Farm type / Categories	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS
		Trailing shoe							*Slurry tooth extirpator/ Shallow injector*						
Gross margin	EUR/ha	864	1,820	6,168	2,679	2,144	2,128	1,650	864	1,811	6,162	2,684	2,144	2,123	1,646
NH_3 total	kg NH_3-N ($\times 10^3$)	974	16,906	5,724	14,131	4,092	41,828	75,190	974	16,370	5,673	14,115	4,045	41,177	73,840
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	-3.4	-1.7	-1.4	-1.7	-2.2	-1.8	--	-3.9	-1.8	-1.5	-1.7	-2.4	-2.0
NH_3 organic[1)]	%	--	-22.6	-6.7	-5.2	-9.8	-13.9	-14.8	--	-25.0	-7.6	-5.3	-10.9	-15.3	-16.5
NH_3 mineral[2)]	%	--	-22.4	--	-3.8	-14.4	-5.2	-2.4	--	-23.1	--	-3.8	-14.7	-5.3	-2.4
PM_{10} total	%	--	--	--	--	--	0.0	0.0	--	--	--	--	--	0.0	0.0
$PM_{2.5}$ total	%	--	--	--	--	--	0.0	0.0	--	--	--	--	--	0.0	0.0
N_2O total	%	--	-4.1	0.4	-1.5	-4.0	-2.2	-1.6	--	-4.7	-0.2	-1.5	-4.0	-2.3	-1.7
CH_4 total	%	--	0.0	0.0	0.0	0.7	0.0	-0.1	--	0.0	0.0	0.0	1.2	0.1	-0.1
CO_2 total	%	--	-1.9	0.0	-0.2	-1.9	-0.5	-0.5	--	-2.0	0.0	-0.2	-2.2	-0.6	-0.6
GHG total	%	--	-1.1	0.1	-0.5	-1.2	-0.7	-0.8	--	-1.2	0.0	-0.5	-1.1	-0.8	-0.8
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	5.4	14.5	11.0	5.7	6.6	6.8	--	5.5	13.3	11.3	5.4	6.7	6.7

b)

Farm type / Categories	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	ST	BW
		Trailing shoe							*Slurry tooth extirpator/ Shallow injector*						
Gross margin	EUR/ha	854	1,680	3,013	1,845	1,353	1,516	1,298	854	1,672	3,010	1,845	1,351	1,515	1,295
NH_3 total	kg NH_3-N ($\times 10^3$)	979	3,351	3,197	78.5	2,069	9,575	26,664	979	2,936	3,191	78.4	2,028	9,213	25,990
		Changes to the reference							**Changes to the reference**						
Gross margin	%	--	-3.2	-1.5	-1.4	-2.0	-1.8	-1.9	--	-3.6	-1.6	-1.4	-2.2	-1.9	-2.1
NH_3 organic[1)]	%	--	-10.2	-8.0	-4.8	-21.9	-12.6	-15.0	--	-24.7	-8.2	-4.9	-26.1	-18.9	-17.5
NH_3 mineral[2)]	%	--	-20.0	-3.5	-1.9	-16.4	-3.3	-2.8	--	-20.1	-3.5	-2.0	-16.5	-3.3	-2.9
PM_{10} total	%	--	--	--	--	--	0.0	0.0	--	--	--	--	--	0.0	0.0
$PM_{2.5}$ total	%	--	--	--	--	--	0.0	0.0	--	--	--	--	--	0.0	0.0
N_2O total	%	--	-4.3	-1.7	-1.1	-5.4	-2.0	-1.9	--	-4.5	-1.7	-1.1	-5.5	-2.1	-1.9
CH_4 total	%	--	0.2	0.0	0.0	0.0	0.2	-0.1	--	0.2	0.0	0.0	0.0	0.3	0.0
CO_2 total	%	--	-4.2	-0.6	-0.4	-2.0	-1.1	-0.8	--	-4.2	-0.6	-0.4	-1.9	-1.1	-0.8
GHG total	%	--	-1.3	-1.0	-4.3	-1.8	-1.0	-1.0	--	-1.3	-1.0	-0.5	-1.5	-1.0	-0.9
		Average abatement costs							**Average abatement costs**						
NH_3 total	EUR/kg NH_3-N	--	8.5	12.3	12.4	6.3	8.3	9.0	--	6.3	13.0	12.5	6.3	7.4	8.6

c)

Categories \ Farm type	Units	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB	AF	FGF	ILF_Pigs	ILF_Poultry	MF	BB
		Trailing shoe						***Slurry tooth extirpator/ Shallow injector***					
Gross margin	EUR/ha	686	1,089	6,930	24,782	827	914	686	1,089	6,923	24,858	825	912
NH_3 total	kg NH_3-N ($\times 10^3$)	2,627	3,661	815	2,756	8,520	18,377	2,627	3,661	812	2,745	8,320	18,164
		Changes to the reference						**Changes to the reference**					
Gross margin	%	--	--	-1.3	-1.7	-1.7	-1.0	--	--	-1.4	-1.4	-1.9	-1.2
NH_3 organic[1)]	%	--	--	-7.7	-3.4	20.1	-11.1	--	--	-8.0	-3.8	-22.9	-12.6
NH_3 mineral[2)]	%	--	--	--	--	-1.6	-0.8	--	--	--	--	-1.8	-1.0
PM_{10} total	%	--	--	--	--	--	0.0	--	--	--	--	--	0.0
$PM_{2.5}$ total	%	--	--	--	--	--	0.0	--	--	--	--	--	0.0
N_2O total	%	--	--	-0.2	-0.1	-1.6	-0.9	--	--	-0.2	-0.1	-1.7	-0.9
CH_4 total	%	--	--	0.0	0.0	-1.9	-1.2	--	--	0.0	0.0	-1.9	-1.5
CO_2 total	%	--	--	0.0	0.0	-0.6	-0.3	--	--	0.0	0.0	-0.7	-0.3
GHG total	%	--	--	-0.1	0.0	-1.4	-0.8	--	--	-0.1	0.0	-1.5	-0.9
		Average abatement costs						**Average abatement costs**					
NH_3 total	EUR/kg NH_3-N	--	--	11.3	11.3	6.7	7.7	--	--	11.7	11.2	6.8	7.8

Notes: [1)] NH_3 losses from manure management; [2)] NH_3 losses from application of mineral fertilizers; [3)] no NH_3 reduction occurs; AF - arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; HA – Hannover, LS – Lower Saxony, FR – Freiburg, BW – Baden-Württemberg, BB – Brandenburg

Environment friendly manure spreading is expensive NH_3 emission abatement measure resulting in overall reduction of gross margin (Tables 43, 44). The reduction rate of *scenario's* financial effect for each study region hardly differs between trailing shoe and slurry injector. In general gross margin reduction in arable Brandenburg is less comparing to the regions with relatively high livestock density, namely Baden-Württemberg, Lower Saxony and their administrative units. This can be explained by a higher amount of agricultural land under manure land application than in Brandenburg (chapter 4). At the farm level, the highest decrease of gross margin is expected forage growing farms in Weser-Ems and Stuttgart (up to 2-4%) and mixed farms in all study regions in Table 44 (up to 2%). No changes occur from the *scenario* implementation for the forage growing farms in Brandenburg, as according to the BAU assumption, livestock there is housed on a deep litter (section 5.6), and **Scenario V** assumptions do not match for spreading of dung and leachate.

Reduction rates of total NH_3 losses increase gradually from comparatively cheap trailing shoe to relatively expensive injector techniques. In Baden-Württemberg, the abatement rates are uppermost, i.e., 14.1%, and 16.2% for the employment of trailing shoe and slurry injector, respectively. Relatively low reduction of total NH_3 emitted in Weser-Ems and Lower Saxony results from higher livestock density, agricultural land endowments and hence greater NH_3 emission potential (Appendixes I, II, and III). Similarly to livestock feeding and manure storage stages of manure management, cut off in NH_3 stemming from manure management is slightly higher than abatement rates for total NH_3 losses (Table 44).

Although total NH_3 emission reduction occurs mainly due to the changes in the NH_3 released from manure management, abatement of NH_3 released from mineral fertilization also contributes to the total NH_3 abatement. It can be justified by a higher amount of N retained in the soil due to the employment of environmentally friendly manure spreading techniques. The respective decrease resulting from trailing shoe and slurry extirpator use reaches 2%, 3%, and 1% in Lower Saxony, Baden-Württemberg, and Brandenburg, correspondingly (Table 44).

Alterations in PM and GHG emissions resulting from the *scenario* implementation are negligible and caused by adjustment of optimal solution to *scenario* conditions (Table 44).

Cost-benefit analysis reveals that the average abatement costs from the slurry spreading with trailing shoe and injector employment hardly differ and reaches 6.8 and 7.8 EUR/kg NH_4-N, respectively, for Lower Saxony and Brandenburg. Controversially, in Baden-Württemberg slurry injection into the arable land is cheaper then spreading of liquid manure with trailing shoe, i.e., 8.6 versus 9.0 EUR/kg NH_3-N. At the farm level, the cheapest NH_3 abatement is detected for forage growing and mixed farms, where the mitigation is the uppermost (Table 44).

Highlighting the content of this section, it can be mentioned that both financial and ecological efficiency of the scenario for NH_3 development varies between regions and farm types. Thus, relatively higher land endowments and livestock density of Lower Saxony and Baden-Württemberg speak for higher emission reduction and lower abatement costs. Regardless its high price injector is the most efficient manure spreading technique, as it results in the lowest NH_3 mitigation costs.

7.5 Abatement of PM Emission: Reduced Tillage (Scenarios VIa and b)

Currently about 7% of total arable land is under no-tillage practises. The fact that European farmers are generally not strongly affected by the consequences of soil degradation and/or water loss is probably one of the main reasons why they are unlikely to adopt conservation tillage (PUTTE *et al.*, 2010; DUXBURY, 1994). The term of conservation tillage covers several soil preparation practises, i.e., no-tillage and mulching. There are reverse opinions on, whether reduced tillage fells into the category of conservation agriculture. Following PUTTE *et al.* (2010), in this study we regard the reduced tillage as the pillar of conservation agriculture. There are differences between no-tillage, mulching and reduced tillage to be explained: no-tillage farming and mulching generally imply refusal of any soil disturbance (occurring, e.g., due to ploughing and/or harrowing), while by reduced tillage only ploughing is excluded.

In the framework of **Scenarios VIa** and **b** reduced tillage practise is checked for its financial and emission abatement efficiency. Financial support per hectare of area under reduced tillage is introduced in the framework of **Scenario VIb**. The funding of 40 EUR and 60 EUR per ha of area under reduced tillage is provided in the framework of environmental regional programs in Lower Saxony and Baden-Württemberg, respectively (section 3.1.3). The share of the area under reduced tillage is not restricted for the *scenarios* analysed in this section. However, one of the BAU assumptions is the employment reduced tillage by German farmers on only 10% of arable land (section 5.6).

The scenario results compared with the BAU outputs are presented in Table 45 for farms in Weser-Ems, Karlsruhe, their respective federal states, and Brandenburg. The size of arable area is chosen as selection criterion for administrative regions.

Table 45 Emissions abatement results from the introduction of reduced tillage, without and with financial aid in Weser-Ems (a), Karlsruhe (b), and Brandenburg (c)

a)

Categories / Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	WE	LS
Arable land	ha ($\times 10^3$)	171	91.9	41.8	219	46.8	570	2,599
Scenario VIa								
Reduced tillage area	ha ($\times 10^3$)	165	53.4	36.3	218	42.4	515	1,296
Gross margin	EUR/ha	1,042	1,918	6,413	2,897	2,286	2,278	1,777
PM_{10} total	kg PM_{10} ($\times 10^3$)	893	918	1,046	7,066	2,196	12,120	24,006
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times 10^3$)	279	376	225	2,017	531	3,429	6,710
Changes to the reference								
Gross margin	%	20.6	1.8	2.2	6.3	4.0	4.8	5.8
PM_{10} total	%	-51.1	-24.7	-14.9	-14.3	-9.8	-19.0	-22.8
$PM_{2.5}$ total	%	-30.0	-11.0	-9.6	-7.1	-5.8	-9.9	-12.1
NH_3 total	%	8.2	-0.5	1.7	0.1	--	0.2	0.3
N_2O total	%	8.5	3.9	2.0	3.5	1.9	4.1	3.4
CH_4 total	%	--	0.6	6.0	--	-0.8	0.6	0.4
CO_2 total	%	8.2	-1.0	4.0	1.5	0.7	2.1	3.9
GHG without CO_2 enclosure	%	8.0	1.0	4.1	1.7	0.2	2.0	2.2
CO_2 enclosure	%	869	322	877	114	81.8	172	51.4
GHG total	%	-78.5	-5.6	-8.9	-38.3	-36.1	-21.3	-21.1
Average abatement costs								
PM_{10} total	EUR/kg PM_{10}	-32.8	-45.2	-40.4	-32.0	-26.5	-33.8	-35.6
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	-255	-296	-310	-244	-194	-254	-273
Scenario VIb								
Reduces tillage area	ha ($\times 10^3$)	165	53.7	37.7	218	42.4	517	1,298
Gross margin	EUR/ha	1,081	1,922	6,444	2,935	2,292	2,294	1,798
PM_{10} total	kg PM_{10} ($\times 10^3$)	893	919	1,104	7,066	2,196	12,179	24,063
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times 10^3$)	279	376	234	2,017	531	3,438	6,720
Changes to the reference								
Gross margin	%	25.1	2.0	2.7	7.7	5.1	5.8	7.0
PM_{10} total	%	-51.1	-24.6	-10.1	-14.3	-9.8	-18.6	-22.6
$PM_{2.5}$ total	%	-30.0	-10.9	-6.1	-7.1	-5.8	-9.7	-12.0
NH_3 total	%	8.2	-7.1	0.4	0.1	--	-3.0	-1.7
N_2O total	%	8.5	3.5	-0.1	3.5	1.9	3.7	3.3
CH_4 total	%	--	0.6	0.0	--	-0.8	0.3	0.1
CO_2 total	%	8.2	-1.0	3.0	1.5	0.7	1.9	3.9
GHG without CO_2 enclosure	%	8.0	1.1	1.6	1.7	0.2	1.7	2.1
CO_2 enclosure	%	869	323	934	115	81.8	173	258
GHG total	%	-78.5	-5.7	-12.0	-38.3	-36.2	-21.7	-21.3
Average abatement costs								
PM_{10} total	EUR/kg PM_{10}	-39.8	-52.1	-73.5	-39.1	-33.4	-41.8	-43.3
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	-310	-343	-602	-298	-244	-315	-332

b)

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	KR	BW
Arable land	ha ($\times10^3$)	82.0	5.7	1.6	2.1	52.2	144	1,404
Scenario VIa								
Reduced tillage area	ha ($\times10^3$)	76.8	3.1	1.1	2.0	50.9	134	719
Gross margin	EUR/ha	789	1,394	7,879	1,772	883	1,013	1,368
PM_{10} total	kg PM_{10} ($\times10^3$)	436	55.0	28.4	175	283	978	6,842
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times10^3$)	134	21.2	5.6	51.0	95.6	307	2,110
Changes to the reference								
Gross margin	%	10.1	1.1	0.0	0.6	7.2	5.8	3.4
PM_{10} total	%	-51.0	-24.2	-17.3	-6.3	-51.9	-44.8	-37.6
$PM_{2.5}$ total	%	-32.3	-11.7	-12.9	-3.4	-31.7	-27.0	-22.0
NH_3 total	%	-5.8	1.5	1.4	0.2	-2.0	-1.0	1.6
N_2O total	%	-3.2	1.6	-0.4	4.1	-1.6	-1.8	-2.4
CH_4 total	%	--	--	--	11.7	0.2	0.9	0.1
CO_2 total	%	-3.7	-2.6	--	-1.1	-5.4	-3.8	-2.3
GHG without CO_2 enclosure	%	-4.7	0.1	-0.1	3.6	-3.3	-2.6	-1.9
CO_2 enclosure	%	837	583	65.6	33.0	876	812	461
GHG total	%	-72.8	-7.7	-16.1	-8.8	-51.6	-46.7	-34.8
Average abatement costs								
PM_{10} total	EUR/kg PM_{10}	-13.1	-27.9	-0.8	-6.2	-14.9	-13.9	-15.0
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	-93.1	-174	-5.6	-41.3	-103	-97.5	-107
Scenario VIb								
Reduced tillage area	ha ($\times10^3$)	82.0	3.4	1.4	2.0	51.1	140	778
Gross margin	EUR/ha	848	8,221	7,923	5,647	1,362	1,473	1,401
PM_{10} total	kg PM_{10} ($\times10^3$)	402	52.7	26.7	175	283	940	6,596
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times10^3$)	129	20.9	5.4	51.0	95.5	302	2,084
Changes to the reference								
Gross margin	%	18.3	1.5	0.6	1.6	12.0	10.1	5.9
PM_{10} total	%	-54.8	-27.4	-22.3	-6.3	-52.0	-47.0	-39.9
$PM_{2.5}$ total	%	-34.4	-13.0	-16.4	-3.4	-31.8	-28.1	-22.9
NH_3 total	%	-5.8	1.6	1.2	1.8	-2.0	-0.8	0.2
N_2O total	%	-3.2	1.6	-0.7	3.9	-1.5	-1.8	-2.8
CH_4 total	%	--	--	--	11.7	0.4	1.1	0.1
CO_2 total	%	-3.9	-2.8	-0.3	-1.0	-5.4	-3.9	-1.4
GHG without CO_2 enclosure	%	-4.8	0.1	0.2	3.6	-3.0	-11.6	-1.7
CO_2 enclosure	%	900	628	114	33	878	592	48.6
GHG total	%	-78.0	-8.3	-27.4	-8.8	-51.5	-48.9	-37.3
Average abatement costs								
PM_{10} total	EUR/kg PM_{10}	-22.1	-34.3	-9.8	-15.2	-24.8	-23.2	-24.9
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	-159	-220	-70.8	-101	-171	-163	-175

c)

Categories \ Farm type	Units	AF	FGF	ILF_ Pigs	ILF_ Poultry	MF	BB
Arable land	ha ($\times10^3$)	446	46.0	8.5	3.5	527	1,030
Reduced tillage area	ha ($\times10^3$)	436	34.8	7.6	3.1	510	992
Gross margin	EUR/ha	718	1,091	7,049	25,261	860	944
PM_{10} total	kg PM_{10} ($\times10^3$)	2,328	365	155	1,509	2,964	7,322
$PM_{2.5}$ total	kg $PM_{2.5}$ ($\times10^3$)	635	129	32.3	442	939	2,177
Changes to the reference							
Gross margin	%	4.6	0.2	0.4	0.2	2.2	2.3
PM_{10} total	%	-51.4	-34.0	-20.9	-1.1	-49.0	-43.1
$PM_{2.5}$ total	%	-35.2	-16.3	-15.0	-0.5	-29.6	-26.2
NH_3 total	%	-0.2	0.3	-1.0	-0.6	2.7	1.2
N_2O total	%	-0.4	0.1	-1.0	-0.2	0.2	-0.1
CH_4 total	%	--	-0.1	--	--	3.6	2.2
CO_2 total	%	-4.2	-0.5	-1.9	-0.1	-2.4	-2.5
GHG without CO_2 enclosure	%	-2.3	-0.2	-1.5	-0.1	0.1	-0.5
CO_2 enclosure	%	132	64.5	-24.8	-1.7	868	134
GHG total	%	-10.7	-1.8	0.8	0.4	-6.2	-6.1
Average abatement costs							
PM_{10} total	EUR/kg PM_{10}	-5.7	-2.3	-5.7	-8.9	-4.6	-5.1
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	-41.0	-16.8	-40.7	-64.5	-33.4	-36.4

Notes: AF – arable farms, FGF – forage growing farms, ILF_Pigs/Poultry – intensive livestock farms with emphasizes on pig and poultry production consequently, MF – mixed farms; WE – Weser-Ems, KR – Karlsruhe, BB – Brandenburg.

The employment of reduced tillage reveals overall increase of gross margin mainly due to a lower diesel amount required for this practise. Because of different technical and production conditions, the gross margin resulting from the **Scenario VIa** implementation in Weser-Ems is more than 2 times higher than in Karlsruhe and Brandenburg. The strongest positive financial effect of the *scenario* is revealed for arable farms in all regions. The uppermost gross margin growth rate in Karlsruhe, i.e., 6% versus 5% in Weser-Ems and ca. 2% in Brandenburg, can be explained by a higher share of arable farms in total arable area in this region, namely, 56% versus 30% in Weser-Ems and 43% in Brandenburg. The positive financial effect of the reduced tillage implementation becomes higher due to the introduction of the financial aid for farmers in the framework of **Scenario VIb**. Comparing to the **Scenario VIa** outputs the gross margin boosts up with a higher rate in Karlsruhe (4.2%) than Weser-Ems (1%). This can be justified by the increase of area under reduced tillage, 4.0% in Karlsruhe versus 0.4% in Weser-Ems (Figure 18).

Expected ecological effect of both scenarios is that PM emissions decrease. Abatement of PM emission is higher in Karlsruhe (45% and 27% for PM_{10} and $PM_{2.5}$, respectively) than in Brandenburg (43% for PM_{10} and 26% for $PM_{2.5}$) and Weser-Ems (19% and 10% for PM_{10} and $PM_{2.5}$, correspondingly), whereof up to 40-50% for PM_{10} and 30-40% for $PM_{2.5}$ stem from arable agriculture in all study regions (Appendixes I, II, and III). Total PM losses diminish thank to the reduction of diesel amount for agricultural machinery and hence less PM emitted from diesel upstream production. Mitigation ratios for PM emission after the premium introduction (**Scenario VIb**) are higher comparing to the results without subventions (**Scenario VIa**) by less than 1.0% in Weser-Ems and by ca. 1.3-3.5% in Karlsruhe.

Alterations in NH_3 losses occur mainly due to the adjustment of optimal solution to *scenarios'* assumptions. The optimized results for crop production structure in *scenarios* and BAU are shown in Figure 17.

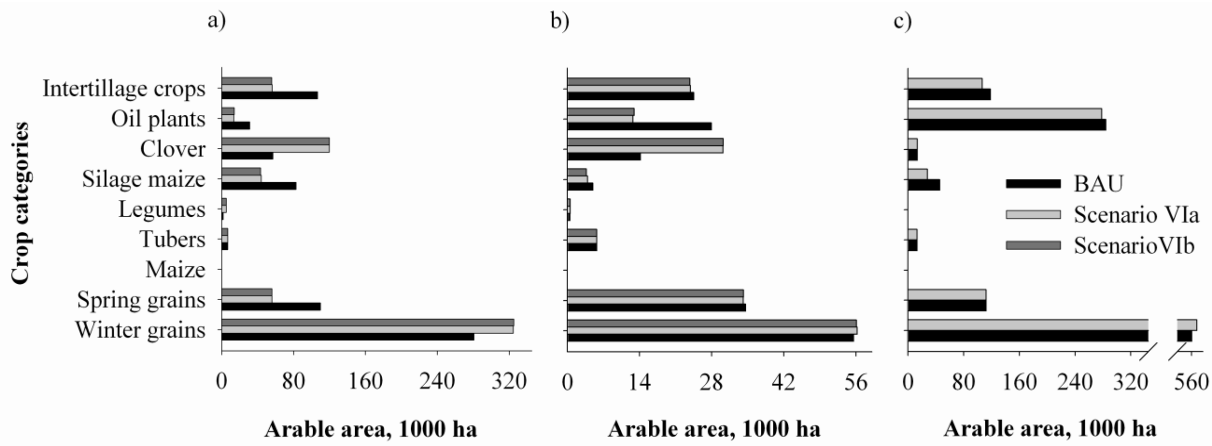


Figure 17 Crop production (in 1000 ha) resulting from BAU and **Scenarios VIa** and **b** for Weser-Ems (a), Karlsruhe (b), and Brandenburg (c)

Important is the positive effect of the reduced tillage practises on the development of GHG emissions. The uppermost GHG abatement resulting from **Scenario VIa** is revealed for Karlsruhe and Baden-Württemberg, i.e., nearly 47% and 35%, respectively, and the lowest for Weser-Ems and Lower Saxony, namely, ca. 21%. The introduction of financial support leads to a higher reduction rate for GHG losses. The drop in total GHG emissions results mainly from C-sequestration in soils and thus CO_2 enclosure; it is nearly twofold higher for Weser-Ems and Brandenburg and nearly 6 times higher in Karlsruhe than in BAU. Nevertheless, without counting for carbon accumulation in soil, CO_2 emissions and GHG losses from agricultural and upstream sector increase by nearly 2% in Weser-Ems and Lower Saxony (Table 45). This can be explained by both adjustment of an optimal crop production structure, greater land endowments available for economic crops and thus higher production of mineral fertilizers and amount of heating oil burned during yield drying (Figure 17).

Figure 17 demonstrates that due to the implementation of **Scenario VIa** and **b**, 50% less spring grains, silage maize and cover crops and nearly 60% less oil crops are produced in Weser-Ems. The increase of area under less costly rye (by 16%) and clover (by over 100%) counterbalance above-mentioned reductions. The less area under oil crops in Karlsruhe (by nearly 50%) is compensated through the double acreage under clover, 2% more area under winter grains and less spring grains produced. In Brandenburg, the uppermost reduction is detected for the area under silage maize (ca. 40%), meanwhile 4.4% more winter grains and 2.2% less winter rapeseed are produced. The discrepancy between regions in the reaction on the scenario assumptions stems from the balancing between crops for animal fodder and crops as market product, and the changes are less in the regions with relatively lower livestock density, e.g., Karlsruhe and Brandenburg (0.4 LU ha^{-1}) comparing to Weser-Ems (1.4 LU ha^{-1}). In addition, production of crops with relatively low requirements for fertilisers and higher area under legumes and clover, maintaining soil N-content, diminishes the need for fertilization.

In Figure 18 effect of **Scenarios VIa** and **b** on the share of arable land under reduced tillage in comparison to BAU for Weser-Ems, Karlsruhe, and Brandenburg is shown.

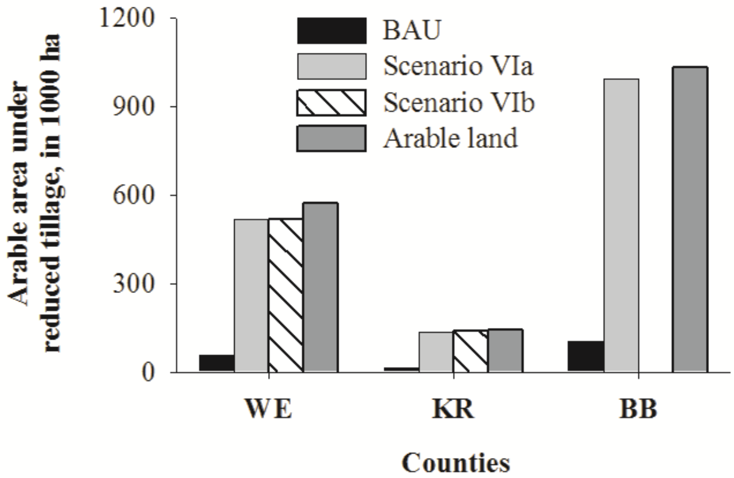


Figure 18 Area under the reduced tillage in BAU and resulted from **Scenario VIa** and **b**, in the comparison to the total arable land

Notes: WE – Weser-Ems, KR – Karlsruhe, BB – Brandenburg

If, according to the BAU assumptions, reduced tillage is applied on 10% of arable land (57, 14 and 103 ha ($\times 10^3$) in Weser-Ems, Karlsruhe, and Brandenburg, correspondingly), unlimited opportunity to implement this type of soil management is followed with tenfold increase of the area under it in all regions. Additional provision of financial support results in a higher increase in arable area under this land preparation practise, but this positive effect of premium is negligible (Figure 18). Thus, the share of reduced tillage area in the total arable land, resulting from **Scenario VIa**, constitutes eventually 90% for Weser-Ems, 93% for Karlsruhe, and 96% for Brandenburg. The implementation of **Scenario VIb** leads to the boost of respective values by 4% and 1% for Karlsruhe and Weser-Ems, respectively.

Generalising it can be said that employment of reduced tillage without restrictions for the area under reduced tillage and with subvention per hectare of respective area assures ca. 50% less PM released from arable farming in the study regions. The abatement of PM emission is related to the positive financial outcome and is the cheapest and the most efficient in the region and farms with higher share of arable land under reduced tillage, like Karlsruhe. The important consequence of reduced tillage practise is the abatement of GHG losses due to carbon sequestration in soil. The mitigation rate for GHG released may reach up to 80% depending on the region and farm type.

7.6 Abatements of PM and NH_3 Emissions: Exhaust Air Treatment

Nowadays the construction of a new animal barn is only possible, when requirements of national and regional environmental law are met and additional pollution abatement options are introduced in livestock houses (section 3.2). Exhaust air (EA) treatment is one of the most efficient measures for reduction of emissions stemming from animal barn. In Germany "Cloppenburg guideline" (Germ., "Cloppenburger Leitfaden") put an official start to the certified practises for filtering of livestock buildings' EA[34]. This guideline established minimal requirements to construction, maintenance and operation of exhaust air treatment systems (EATS), and NH_3, PM, and odour abatement. In 2005 "Cloppenburg guideline" was substituted with DLG Signumtest[35]. Due to its optional character, employment of EATS in general and certified[36] ones particularly is rather limited to individual cases (HAHNE *et al.*, 2007; SCHIER, 2005).

[34] Exhaust (EA) is the air, which leave animal barn through ventilation and air conditioning or free aeration systems. A release of the exhaust air out of the livestock house causes certain emissions, which depend on the composition of air (SCHIER, 2005).

[35] Germ., Baumuster- und Gebrauchswertprüfung zur Zertifizierung von Abluftreinigungsanlagen der DLG e.V.

[36] Personal communication with Winfried Gramatte, contact person in the fields as job safety, quality management, renewable energy, DLG, from 13.08.2010; personal communication with Jochen Hahne, TI, from 10.05.2010

7.6.1 Scenario VIIa

The objective of **Scenario VIIa** is to determine financial and abatement effect from employment of different EATSs in pig barns. Functioning of filters analysed in this *scenario* is based on a primary air cleaning process, i.e., physical, chemical, and biological, and secondary principle, e.g., physical air cleaning by bio-filter (SCHIER, 2005).

Abatement potentials for both PM and NH_3 are taken from KTBL (2008b) for five filter types. However, these data are very restrictive for future forecast of PM emission, as mitigation efficiency for PM is presented for the total dust rather than for different fractions. To fill this gap, additional assumptions on abatement of PM_{10} and $PM_{2.5}$ are made and together with abatement potentials for NH_3 losses presented in Table 46.

Table 46 Mitigation potentials (in %) for PM and NH_3 for different EATS types

Sources	**KTBL (2008b)**		**own assumptions based on KTBL (2008b) and personal communications***		
	PM	**NH_3**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Single stage biofilters	>70	--	70-90	30-90	--
Trickle bed reactors	>70	>70	70-90	30-90	70-90
Single-stage chemical scrubber	>70	70-95	70-90	30-90	70-95
Two-stage chemical scrubber	>70	70-89	70-90	30-90	70-89
Three-stage chemical scrubber	>70	70-95	70-90	30-90	70-95

Note: * more information is in the text.

Measurements of PM_{10} emissions can be characterized as relatively precise, and it is assumed that at least 70% of PM_{10} is captured with EATS. Nevertheless, the same cannot be said about the $PM_{2.5}$ measurements, firstly, due to the novelty of the interest to $PM_{2.5}$ emission, which became a subject to discussions only in 2005. Secondly, there are still analytical obstacles related to measuring of $PM_{2.5}$ captured by filters: release and following drying out of water aerosols leads to salts' deposition on the filter surface and hence increases dust load[37]. This can explain often resulting low or negative $PM_{2.5}$ abatement potential. Therefore, minimal $PM_{2.5}$ emission reduction is assumed to be at least 30% and maximal abatement ratio equal to 90% for both PM fractions (Table 46). For comparison, MELSE *et al.* (2008) states that an average PM_{10} and $PM_{2.5}$ abatement potential of multi-pollutant exhaust air scrubbers is about 62-93% and 47-90%, correspondingly. In general, NH_3 and PM emissions reduction from filtering of EA depends rather on a proper operation of EATS than on the filter type (OGINK *et al.*, 2007; KTBL, 2008b).

[37] Personal communication with Jochen Hahne, TI, from 10.05.2010

Standard capacities of EATS for this *scenario* are chosen depending on number of pig places from KTBL (2008b) and GRIMM (2010), their full installation and operation costs from KTBL (2008b, 2005) (for chemical scrubbers), and GRIMM (2010) (for filtering capacities for 3000 animal places). This *scenario* operates with the costs of certified filters in new-built animal barns. Expenses related to adjustment of livestock house for EATS' installation may vary widely depending on barn design and technical conditions (KTBL, 2008b). For instance, an installation of filters in animal house with decentralized ventilation requires changing of a whole ventilation system. This adjustment can be so expensive that the employment of EATS may become unprofitable[38]. OGINK *et al.* (2008) estimates additional costs for necessary modification in existing animal barn for filter installation: they are higher by 31-41% for sows and by 26-34% for fattened pigs than the costs for setting up of EATS in a new-built barn (OGINK *et al.*, 2008).

Annual EATS costs comprise fixed and variable costs. Fixed or investment costs including depreciation and interest rate and depending on filter capacity can be subdivided into costs for filter base construction and EATS mounting. Variable or operational costs are related to maintenance and utilization of electricity, water, acids, wastewater, and labour (KTBL, 2008b; SCHIER, 2005; MELSE *et al.*, 2009a). The investment and operational costs for fattened pigs in litterless houses are recalculated for breeding sows (KTBL, 2008b). There is no information on investment requirements for EATS installation in poultry houses and filter operational costs for fattened pig barns cannot be calibrated for poultry[39] due to different composition of EA (KTBL, 2008b). This together with the fact that EATS are applied to lesser extend in poultry barns, because of a high dust and feathers load (KTBL, 2008b, 2005) explains, why the *scenario* is implemented only for pigs producing farms.

Due to operation of scrubbers and trickle bed reactors NH_3 content in EA reduces and ca. 1.7 kg of N per fattened pig place per annum is accumulated in wastewater (KTBL, 2008b). The scrubbing water serves as a potential fertilizer. To determine imputed income from saving on mineral fertilizers, the prices per 1 kg of calcium ammonium nitrate and urea are calibrated with their N-shares into prices for 1 kg of N. Resulting values are weight with the fertilizers' domestic sale (Table 30) to obtain the average price of 1.04 EUR/kg N. It is assumed that the same amount of N is accumulated in filter wastewater (ca. 1.7 kg N per animal place per annum) in barns with fattened pigs and breeding sows. Thus, the savings from land application

[38,39] Personal communication with Ewald Grimm, Dipl.-Ing. techn. Umweltschutz, KTBL, from 13.08.2010

of this water instead of mineral fertilizers are equivalent to 1.84 EUR per pig place per annum. However, EATS wastewater must be stored, and in this scenario it is assumed that scrubbing water from EA filtering is stored in slurry storage enlarged for 0.76 EUR per animal place (ap) per annum (a) (KTBL, 2008b) (section 7.6.3).

For **Scenario VIIa** it is assumed that 100% of German farms employ EATSs. Tables 47-49 and Appendixes I, II, and III demonstrate the results from installation of EATSs for intensive livestock farms in chosen administrative units in Lüneburg, Karlsruhe, their federal states and Brandenburg. High number of pig places per farm serves as a selection criterion for the study regions. When both pigs categories are present at the intensive livestock farm, capacity of EATSs are adjusted for each animal type. If fattened pig and sow production occurs at separate farms, the results for two farm categories are shown (Tables 47-49).

Table 47 Impact of EATS installation on the example of a typical intensive livestock farm with the emphasis on pig production (861 fattened pigs' and 153 sows' places per farm) in Lüneburg

	Units	Trickle bed reactor		2-stage system[1]		3-stage system[2]		Biofilter		Chemical scrubber		3-stage system[3]	
Standard unit capacities	ap[4]	1,060	460	1,060	460	1,060	460	1,060	460	1,060	460	1,060	460
for fattened pigs		×	--	×	--	×	--	×	--	×	--	×	--
for sows		--	×	--	×	--	×	--	×	--	×	--	×
Gross margin	EUR/ha	4,477		4,469		4,566		4,861		4,783		4,541	
Investment costs[5]	EUR/ap	7.2	22.1	11.5	28.2	7.1	21.8	3.1	7.5	6.0	13.6	7.8	24.0
Operational costs[6]	EUR/ap	16.4	30.1	11.2	29.8	10.8	32.8	3.6	8.7	5.4	13.2	11.3	31.9
Total costs[5]	EUR/ap	23.6	52.2	22.7	58.0	17.9	54.6	6.6	16.2	11.4	26.8	19.1	55.9
Scenario results													
PM_{10}	kg ($\times 10^3$)	801		801		801		804		801		801	
$PM_{2.5}$	kg ($\times 10^3$)	176		176		176		180		176		176	
NH_3 organic[7]	kg ($\times 10^3$)	1,516		1,519		1,498		3,733		1,498		1,498	
NH_3 mineral[8]	kg ($\times 10^3$)	439		440		439		519		439		439	
Changes to the reference													
Gross margin	%	-13.4		-13.5		-11.6		-5.9		-7.5		-12.1	
PM_{10}	%	-26.1		-26.1		-26.1		-25.8		-26.1		-26.1	
$PM_{2.5}$	%	-17.9		-17.9		-18.0		-16.3		-18.0		-18.0	
NH_3 org	%	-59.4		-59.3		-59.9		--		-59.9		-59.9	
NH_3 min	%	-15.4		-15.4		-15.5		--		-15.5		-15.5	
N_2O	%	-7.7		-7.7		-7.7		--		-7.7		-7.7	
CH_4	%	--		--		--		--		--		--	
CO_2	%	-3.0		-3.0		-3.0		--		-3.0		-3.0	
GHG	%	-4.1		-4.1		-4.2		--		-4.2		-4.2	
Average abatement costs													
PM_{10}	EUR/kg PM_{10}	76.8		77.8		66.9		34.5		42.8		69.8	
$PM_{2.5}$	EUR/kg $PM_{2.5}$	565		572		492		276		315		512	
NH_3 total	EUR/kg NH_3-N	9.5		9.6		8.2		--		5.2		8.5	

Notes: [1] 2-stage filter with chemical and water cleaning; [2] 3-stage chemical scrubber with chemical, water and biofiltering stage; [3] 3-stage chemical scrubber with chemical and 2× water cleaning steps; [4] ap – animal places; [5] annual costs calculated on the basis of KTBL (2008b), inclusive the costs for the slurry storage enlargement; [6] annual costs calculated on the basis of KTBL (2008b); [7] NH_3-N emissions sourced from manure management; [8] NH_3-N emissions from mineral fertilizers land application

Table 48 Impact of EATS installation on the example of a typical intensive livestock farm with the emphasis on pig production (215 sows' places per farm) (a) and farm with the emphasis on poultry production (511 fattened pigs' places per farm) (b) in Karlsruhe

a)

	Units	Trickle bed reactor	2-stage system[1)]	3-stage system[2)]	Biofilter	Chemical scrubber	3-stage system[3)]
Standard unit capacity	ap[4)]	460	460	460	460	460	460
Gross margin	EUR/ha	7,255	7,222	7,243	7,484	7,414	7,233
Investment costs[5)]	EUR/ap	16.0	20.3	15.0	5.4	9.9	17.3
Operational costs[6)]	EUR/ap	21.4	21.2	23.3	6.2	9.4	22.7
Total costs[5)]	EUR/ap	37.4	41.5	38.3	11.5	19.3	40.0
Scenario results							
PM_{10} total	kg ($\times 10^3$)	23.2	22.9	23.2	22.9	23.2	23.2
$PM_{2.5}$ total	kg ($\times 10^3$)	4.8	4.7	4.8	4.7	4.8	4.8
NH_3 organic[7)]	kg ($\times 10^3$)	108	109	107	175	109	113
NH_3 mineral[8)]	kg ($\times 10^3$)	4.9	4.9	4.9	4.8	4.9	4.9
Changes to the reference							
Gross margin	%	-7.9	-8.3	-8.0	-5.0	-5.8	-8.1
PM_{10} total	%	-20.6	-21.9	-20.6	-22.0	-20.6	-20.6
$PM_{2.5}$ total	%	-13.9	-15.1	-13.9	-15.2	-13.9	-13.9
NH_3 organic	%	-47.6	-46.7	-47.8	-14.8	-47.0	-45.1
NH_3 mineral	%	-12.0	-12.0	-12.1	-13.8	-12.1	-12.1
N_2O	%	-5.9	-4.3	-4.9	-6.0	-6.1	-4.3
CH_4	%	--	-1.7	--	-1.7	--	--
CO_2	%	-1.0	-2.6	-1.0	-2.7	-1.0	-1.0
GHG	%	-4.0	-4.3	-3.5	-4.4	-4.1	-3.1
Average abatement costs							
PM_{10} total	EUR/kg PM_{10}	170	169	174	101	127	176
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	1,323	1,287	1,349	765	984	1,369
NH_3 total	EUR/kg NH_3-N	10.5	11.2	10.6	--	7.9	11.4

b)

	Units	Trickle bed reactor	2-stage system[1)]	3-stage system[2)]	Biofilter	Chemical scrubber	3-stage system[3)]
Standard unit capacity	ap[4)]	700	700	700	700	700	700
Gross margin	EUR/ha	1,569	1,560	1,524	1,680	1,632	1,563
Investment costs[5)]	EUR/ap	12.0	13.8	14.4	6.0	9.4	12.6
Operational costs[6)]	EUR/ap	15.2	14.8	19.3	6.0	8.8	15.9
Total costs[5)]	EUR/ap	27.2	28.6	33.7	12.0	18.2	28.5
Scenario results							
PM_{10} total	kg ($\times 10^3$)	163	163	163	165	163	163
$PM_{2.5}$ total	kg ($\times 10^3$)	49.2	49.2	49.2	49.6	49.2	49.2
NH_3 organic[7)]	kg ($\times 10^3$)	202	202	200	272	200	261
NH_3 mineral[8)]	kg ($\times 10^3$)	0.3	0.3	0.3	0.2	0.3	0.2
Changes to the reference							
Gross margin	%	-10.9	-11.4	-13.4	-5.0	-7.3	-11.3
PM_{10} total	%	-10.9	-10.9	-10.9	-9.9	-10.9	-10.9
$PM_{2.5}$ total	%	-4.8	-4.8	-4.8	-4.1	-4.8	-4.8
NH_3 organic	%	-34.2	-34.1	-34.9	-11.6	-34.9	-32.6
NH_3 mineral	%	31.8	31.6	32.8	344	32.8	--
N_2O	%	-4.3	-4.3	-4.4	-4.7	-4.4	-1.9
CH_4	%	10.3	11.8	10.3	10.8	10.3	10.3
CO_2	%	--	--	--	--	--	--
GHG	%	3.1	3.7	3.1	3.2	3.1	3.7
Average abatement costs							
PM_{10} total	EUR/kg PM_{10}	69.0	72.3	85.0	32.0	46.2	72.2
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	552	579	680	271	369	577
NH_3 total	EUR/kg NH_3-N	13.1	13.8	15.9	--	8.6	14.1

Notes: [1)] 2-stage filter with chemical and water cleaning; [2)] 3-stage chemical scrubber with chemical, water and biofiltering stage; [3)] 3-stage chemical scrubber with chemical and 2× water cleaning steps; [4)] ap – animal places; [5)] annual costs calculated on the basis of KTBL (2008b), inclusive the costs for the slurry storage enlargement; [6)] annual costs calculated on the basis of KTBL (2008b); [7)] NH_3-N emissions sourced from manure management; [8)] NH_3-N emissions from mineral fertilizers land application

Table 49 Impact of EATS installation on the example of a typical intensive livestock farm with the emphasis on pig production (171 fattened pigs' and 1,097 sows' places per farm) (a) and farm with the emphasis on poultry production (3,124 fattened pigs and 476 sows places per farm) (b) in Brandenburg

a)

	Units	Trickle bed reactor		2-stage system[1)]		3-stage system[2)]		Biofilter		Chemical scrubber		3-stage system[3)]	
Unit capacities	ap[4)]	460	1180	460	1180	460	1180	460	1180	460	1180	460	1180
for fattened pigs		×	--	×	--	×	--	×	--	×	--	×	--
for sows		--	×	--	×	--	×	--	×	--	×	--	×
Gross margin	EUR/ha	6,545		6,552		6,584		6,955		6,643		6,492	
Investment costs[5)]	EUR/ap	19.8	7.3	25.3	10.6	19.6	7.0	6.7	4.1	12.2	8.4	21.5	11.7
Operational costs[6)]	EUR/ap	26.9	16.2	26.6	10.8	29.3	11.2	7.8	4.7	11.8	6.9	28.5	17.9
Total costs[5)]	EUR/ap	46.7	23.5	51.9	21.4	48.9	18.2	14.5	8.8	24.1	14.5	50.0	29.6
Scenario results													
PM_{10} total	kg ($\times 10^3$)	150		150		148		144		150		150	
$PM_{2.5}$ total	kg ($\times 10^3$)	34.4		34.4		34.1		31.0		34.4		34.4	
NH_3 organic[7)]	kg ($\times 10^3$)	554		555		546		884		543		543	
NH_3 mineral[8)]	kg ($\times 10^3$)	155		155		155		88.5		155		155	
Changes to the reference													
Gross margin	%	-6.8		-6.7		-6.2		-0.9		-5.4		-7.5	
PM_{10} total	%	-18.5		-18.5		-19.5		-21.8		-18.5		-18.5	
$PM_{2.5}$ total	%	-12.9		-12.9		-13.7		-21.5		-12.9		-12.9	
NH_3 organic	%	-47.8		-47.7		-48.6		-16.8		-48.8		-48.8	
NH_3 mineral	%	-12.4		-12.4		-12.5		-50.1		-12.5		-12.5	
N_2O	%	-6.4		-6.4		-6.4		-6.3		-6.4		-6.4	
CH_4	%	--		--		-1.5		-1.5		--		--	
CO_2	%	-4.2		-4.2		-5.1		-4.7		-4.2		-4.2	
GHG	%	-5.0		-5.0		-5.7		-5.9		-5.0		-5.0	
Average abatement costs													
PM_{10} total	EUR/kg PM_{10}	120		119		105		14.1		95.4		134	
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	804		792		696		66.5		637		892	
NH_3 total	EUR/kg NH_3-N	7.7		7.6		7.0		--		6.0		8.4	

b)

	Units	Trickle bed reactor		2-stage system[1)]		3-stage system[2)]		Biofilter		Chemical scrubber		3-stage system[3)]	
Unit capacities	ap[4)]	3000	700	3000	700	3000	700	3000	700	3000	700	3000	700
for fattened pigs		×	--	×	--	×	--	×	--	×	--	×	--
for sows		--	×	--	×	--	×	--	×	--	×	--	×
Gross margin	EUR/ha	22,587		22,213		22,740		22,107		23,159		22,779	
Investment costs[5)]	EUR/ap	7.3	12.9	7.7	14.8	5.6	15.4	6.0	5.6	6.9	10.1	6.4	13.4
Operational costs[6)]	EUR/ap	9.0	16.3	11.4	15.9	8.0	20.7	12.6	6.5	6.1	9.4	7.9	17.1
Total costs[5)]	EUR/ap	16.3	29.2	19.1	30.7	13.6	36.1	18.6	12.1	13.0	19.5	14.3	30.5
Scenario results													
PM_{10} total	kg ($\times 10^3$)	539		540		540		542		540		540	
$PM_{2.5}$ total	kg ($\times 10^3$)	126		126		126		128		126		126	
NH_3 organic[7)]	kg ($\times 10^3$)	659		660		652		1,457		652		652	
NH_3 mineral[8)]	kg ($\times 10^3$)	280		280		280		331		280		280	
Changes to the reference													
Gross margin	%	-10.4		-11.9		-9.8		-12.3		-8.1		-9.7	
PM_{10} total	%	-16.6		-16.4		-16.4		-16.0		-16.4		-16.4	
$PM_{2.5}$ total	%	-10.9		-10.8		-10.8		-9.1		-10.8		-10.8	
NH_3 organic	%	-54.8		-54.7		-55.2		--		-55.2		-55.2	
NH_3 mineral	%	-15.4		-15.4		-15.5		--		-15.5		-15.5	
N_2O	%	-6.9		-6.8		-6.9		--		-6.9		-6.9	
CH_4	%	-0.3		--		--		--		--		--	
CO_2	%	-4.3		-4.0		-4.0		--		-4.0		-4.0	
GHG	%	-4.8		-4.6		-4.6		--		-4.6		-4.6	
Average abatement costs													
PM_{10} total	EUR/kg PM_{10}	46.5		53.8		44.4		57.0		36.8		43.7	
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	323		374		308		456		256		303	
NH_3 total	EUR/kg NH_3-N	5.9		6.7		5.5		--		4.6		5.4	

Notes: 1) 2-stage filter with chemical and water cleaning; 2) 3-stage chemical scrubber with chemical, water and biofiltering stage; 3) 3-stage chemical scrubber with chemical and 2× water cleaning steps; 4) ap – animal places; 5) annual costs calculated on the basis of KTBL (2008b), inclusive the costs for the slurry storage enlargement; 6) annual costs calculated on the basis of KTBL (2008b); 7) NH_3-N emissions sourced from manure management; 8) NH_3-N emissions from mineral fertilizers land application

Scenario analysis revealed that total annual EATS installation costs per livestock intensive farm with emphasis on pig production in Lüneburg vary between 6.6 and 22.8 EUR per fattening place, and 2.6 and 8.8 EUR per fattening cycle. This is cheaper comparing to the annual costs per sow place, i.e., 16.2-58.0 EUR (Table 47). The filtering capacities vary between two types of intensive livestock farms in Karlsruhe and Brandenburg. Yearly EATS installation cost for pig producing farms in Karlsruhe constitute around 11.5-41.5 EUR per sow, between 12.0 and 33.7 EUR per fattened pig place or 4.7 and 13.1 EUR per fattening cycle (Table 48a, b). Total filter costs by intensive livestock farms with the emphasis on pig production in Brandenburg constitute ca. 14.5-51.9 EUR/ap for fatteners or 5.6-19.7 EUR per fattening cycle and only for 8.8-29.6 EUR per sow place. Controversially, the EATS employment in pig house at intensive livestock farm with the orientation on poultry production is more expensive for sows (in average 26.3 EUR/ap) than for fattened pigs (in average 19.0 EUR/ap or 7.3 EUR per fattening cycle) (Table 49a, b). Such discrepancy in annual EATS costs between two animal types and farm categories can be justified by different number of animal places: the higher the number of pig places the lower the respective costs. Independently on number of animal places, farm type, and region, the lowest annual costs results from the installation of biofilters and the highest costs arise from the employment of trickle bed rectors. The reduction of pig places by 50% assures the increase of relative costs by 100%.

The main sources of the total PM emissions are animal husbandry and upstream production. After installation of different EATS at pig farms in Lüneburg, PM emission of 1.1 kg PM_{10}/ap and 0.3 kg $PM_{2.5}$/ap reduces by up to 26% for PM_{10} and 18% for $PM_{2.5}$ with slightly lower ratios for biofilters. Sow production in Karlsruhe results in nearly 1.6 kg PM_{10}/ap and 0.3 kg $PM_{2.5}$/ap and emission abatement of up to 22% and 15% for PM_{10} and $PM_{2.5}$, respectively. The respective figures for fattened pigs in Karlsruhe are higher, ca. 3.2 kg PM_{10}/ap and 1.0 kg $PM_{2.5}$/ap, and correspond with lower PM losses cut off, ca. 11% for PM_{10} and 5% for $PM_{2.5}$. Emissions of PM per animal place in Brandenburg, i.e., 2.0 kg PM_{10}/ap and 0.5 kg $PM_{2.5}$/ap, hardly differ between two intensive livestock farms. However, the abatement by the farm with emphasis on poultry production is lower than for pig producing farms, i.e., 16% for PM_{10} and 11% for $PM_{2.5}$ versus 19-22% for PM_{10} and 13-22% for $PM_{2.5}$ (Table 49b). Employment of biofilter at the farms with sow production in Karlsruhe and Brandenburg leads to higher PM reduction comparing to the farms producing fattened pigs (Tables 48a, b and 49 a, b). This can be explained by higher PM emission intensity of breeding sows.

Losses of NH_3 from manure management constitute 2.2 kg NH_3-N/ap in Lüneburg. Due to relatively low number of pig places, respective emissions for sow and fattened pigs producing farms in Karlsruhe (7.9 and 5.1 kg NH_3-N/ap) are higher than in Brandenburg (7.0 and 2.5 kg NH_3-N/ap). As biofilters are primarily designed for only PM and odour abatement, their employment does not directly affect NH_3 emissions (section 2.1.2.3). The alterations of total NH_3 released from the management of organic manure in Karlsruhe and Brandenburg can be explained by adjustments of optimal modelling solution to scenario assumptions. Installation of other EATS types in animal barns results in NH_3 emission reduction of 54% in Lüneburg, ca. 47% and 44% for sow producing farms and 35% and 48% for fattened pig producing farms in Karlsruhe and Brandenburg, correspondingly. Total NH_3 abatement depends on the decrease of NH_3 released from mineral fertilisation and manure management, where the reduction rates for the latter are slightly higher than for the total NH_3 emission. Discrepancies in NH_3 mitigation between filter types are negligible (Tables 47-49, Appendixes I, II, and III).

Less NH_3 losses from mineral fertilization are expected due to a partial substitution of mineral fertilizers with filter wastewaters; the exception is employment of biofilters. Thereafter, the amount of not easily breakable N retained after manure land application is higher comparing to the respective BAU results by about 0.22% for livestock intensive farm with the emphasis on pig production in Brandenburg and Lüneburg. Thus, up to 7.0 ($\times 10^3$) EUR and 24.7 ($\times 10^3$) EUR for mineral fertilization can be saved annually by these farms in Brandenburg and Lüneburg. Controversially, in Karlsruhe, these expenses for mineral fertilisation increase by 1.5 ($\times 10^3$) EUR, for N content in manure applied to the land there declines by ca. 0.24% for sow producing farms.

As it is mentioned in section 2.1.2.3, EATS analysed in this study and listed in Table 46 are not designed for abatement of GHG emission. The reduction in GHG emissions by livestock intensive farms in Lüneburg, Karlsruhe, and Brandenburg reaches 4-5%. Decrease in amount of GHG released can be mainly justified by the cut off in N_2O and CH_4 losses occurring due to the adjustment of EFEM conditions to scenario assumptions.

Financial results of emission abatement differ depending on type of farm and EATS. The cheapest PM abatement for almost all intensive livestock farms in study regions occurs due to biofilters employment, i.e., from 32 to 101 EUR/kg PM_{10} and from 276 to 765 EUR/kg $PM_{2.5}$. Exceptional case is the installation of biofilter at fattened pigs producing farms in Brandenburg. In Karlsruhe and Brandenburg, the most costly PM and NH_3 emission reduction follows installation of 3-stage EATS, i.e., 85-134 EUR/kg PM_{10}, 680-892 EUR/kg $PM_{2.5}$ and 16-8 EUR/kg NH_3-N. The abatement of both PM and NH_3 is the cheapest in all regions due to chemical scrubber employments, namely, 43-127 EUR/kg PM_{10}, 315-984 EUR/kg $PM_{2.5}$, and

5-8 EUR/kg NH_3-N. In Lüneburg and Brandenburg the most costly PM and NH_3 reduction results from the installation of 2-stage filter: ca. 78 EUR/kg PM_{10}, 572 EUR/kg $PM_{2.5}$ and 10 EUR/kg NH_3-N in Lüneburg and 47 EUR/kg PM_{10}, 323 EUR/kg $PM_{2.5}$ and 7 EUR/kg NH_3-N in Brandenburg (Tables 47-49).

7.6.2 Simulations of Emission Intensities (Scenario VIIb)

As it has already been mentioned before, EATSs' abatement efficiency is determined by the way to operate them. If in the **Scenario VIIa** mean values for emission reduction ratios have been used for the calculation, the aim of **Scenario VIIb** is to show, how emission development and average abatement costs change due to the employment of different filters by minimal and maximal PM and NH_3 abatement potentials. The *scenario* results along with BAU outputs are presented in Figures 19 and 20.

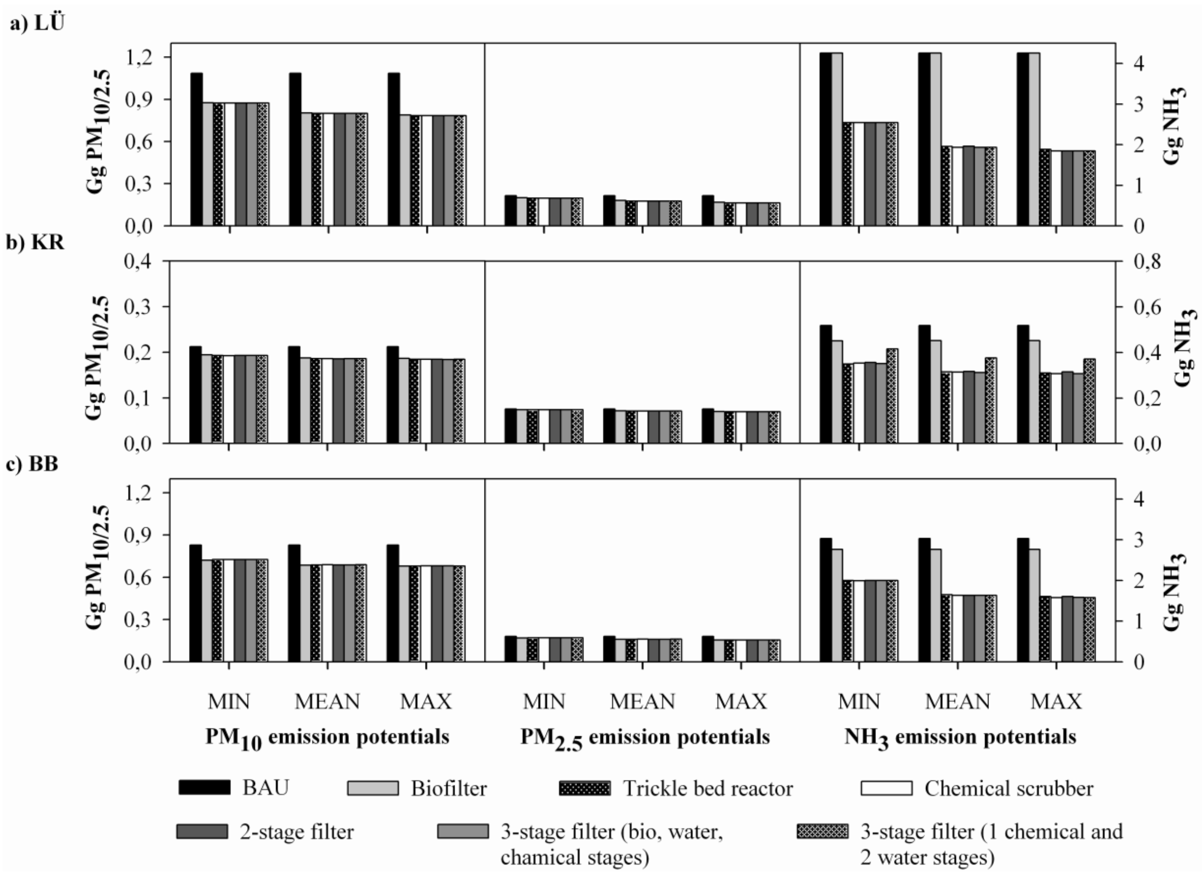


Figure 19 Emissions of PM and NH_3 (in Gg) resulting from the incorporation of minimal, medium and maximal EATS emission abatement ratios into EFEM, in Lüneburg (a), Karlsruhe (b), and Brandenburg (c)

Emission of PM resulting from the modelling with minimal filter abatement efficiency deviates from outcomes resulting from integration of the mean value of emission reduction potential (**Scenario VIIa**) into EFEM by +12%, +4%, and +7% for Lüneburg, Karlsruhe, and Brandenburg, respectively. Particulate matter emissions increase with twofold lower rates due to the EFEM calculations with the maximal abatement potential. Introduction of the maximal PM mitigation rate of 90% assures the lowest PM emissions in all regions. In the case of NH_3 mitigation the introduction of minimal NH_3 reduction ratio into EFEM results in emission outcomes variation of 13% for Karlsruhe to 22% for Brandenburg and 31% for Lüneburg from results of modelling with mean NH_3 abatement ratio (Figure 19).

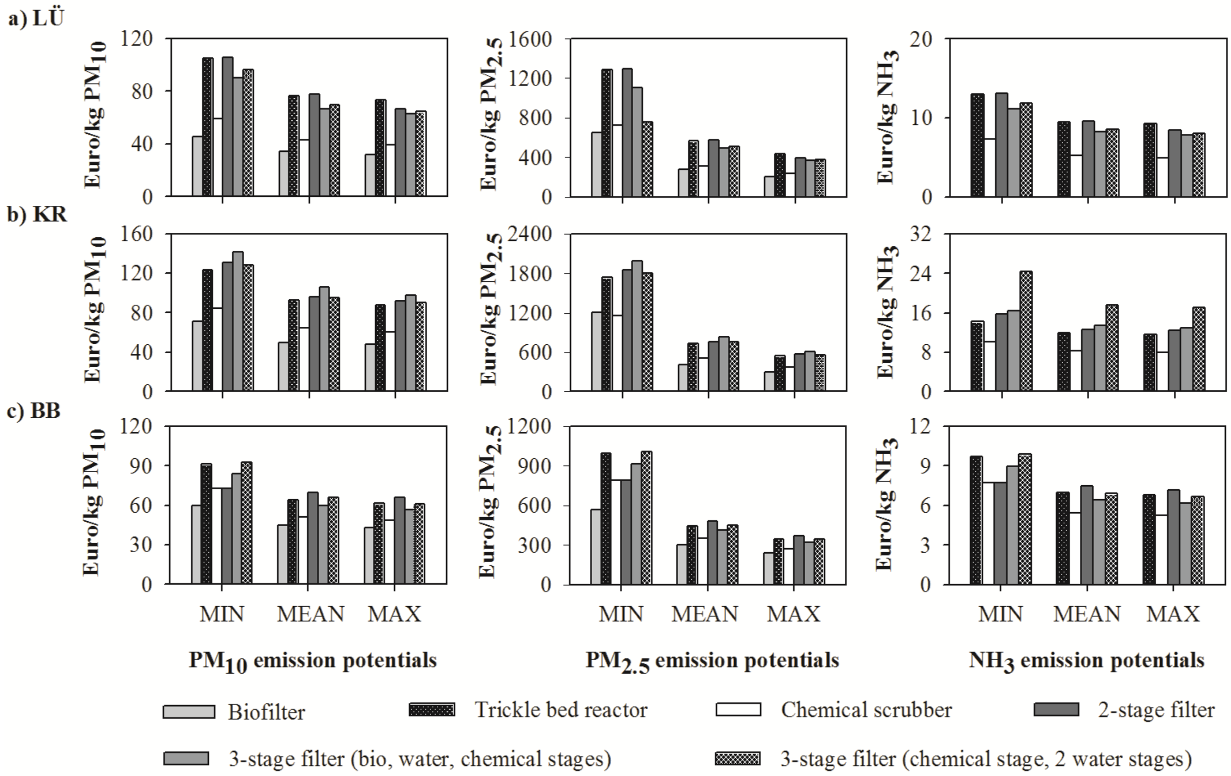


Figure 20 Average costs of PM and NH_3 reduction (in EUR per kg of respective pollutant) resulting from the incorporation of different EATS emission abatement ratios, i.e., minimal, medium and maximal, into EFEM, in Lüneburg (a), Karlsruhe (b), and Brandenburg (c)

Average costs for PM and NH_3 emission abatement resulting from installation of different EATSs differentiate more from each other than the absolute emissions. This can be justified by higher deviation of EATS cost from one filter type to another. These costs are lower for modelling with maximal mitigation ratios comparing to calculations with minimal abatement rates by nearly 33%, 70%, and 30% for PM_{10}, $PM_{2.5}$, and NH_3, respectively (Figure 20).

7.6.3 Simulations of Costs for EATS' Wastewater Storage (Scenario VIIc)

Additional amount of N released with wastewater discharged due to EATS operation must be stored. There are two alternatives for its storage: firstly, it can be added into slurry storage confinement; this requires enlargement of slurry storage (section 7.6.1). Secondly, filter washing water can be placed in the separate storage; however, this is bound with much higher costs. Functioning principle of trickle bed rector allows only direct discharge of wastewater into slurry tank. The solution of ammonium sulphate is released due to the operation of chemical/acid and multiple-stage filters with sulphuric acid addition during chemical stage. Thus, the scrubbing water cannot be directly added to the slurry storage, due to the risk of toxic substances' microbial formation and CO_2 release (KTBL, 2008b). In this case a separate storage facility has to be constructed for wastewater storage. However, if non-sulphuric acid is utilized during chemical stage, the scrubbing water can be directly added to slurry storage tanks. The costs for slurry storage enlargement, i.e., 0.76 EUR per animal place per annum, and construction of new storage, namely 2.61 EUR per animal place per annum, are taken from KTBL (2008b).

Taking into account the amount of N per animal saved through inclusion of EATS washing water into manure management (section 7.6.1), it is important to check, how each option for wastewater storage affects the financial efficiency of abatement measure regarded in this section. For previous *scenarios* (**Scenarios VIIa** and **b**) it was assumed that scrubbing water is stored in enlarged slurry tanks. In the framework of **Scenario VIIc**, the results of introduction of separate wastewater storage are compared with the **Scenario VIIa** and shown in Figure 21 along with the number of fattened pig and breeding sow places.

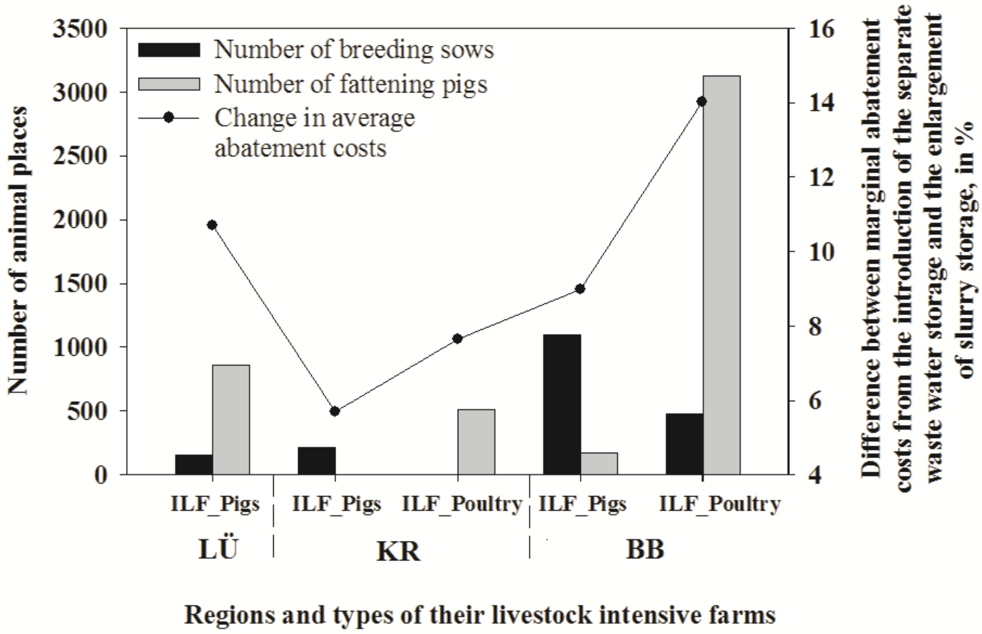


Figure 21 Changes of average abatement costs due to the separate wastewater storage construction versus the slurry storage enlargement (in %) and number of sows' and fattened pigs' places by different types of intensive farms in Lüneburg, Karlsruhe, and Brandenburg.

Notes: LÜ – Lüneburg, KR – Karlsruhe, BB – Brandenburg, ILF_Pigs and ILF_Poultry – intensive livestock farms with the emphasis on pigs and poultry production, correspondingly

As it can be seen from Figure 21 average abatement costs resulting from installation of separate storage facility for filter scrubbing water are certainly higher than financial abatement efficiency resulting from the enlargement of slurry storage. The costs augmentation ratios vary between regions and intensive livestock farms and constitute ca. 11% for Lüneburg, 5-8% for Karlsruhe, and 9-14% for Brandenburg. Farms with higher number of fattened pigs demonstrate an increase in average abatement costs (Figure 21).

Underlying the results of all respective *scenarios* (VIIa, b and c) presented in section 7.6, it has to be mentioned that EATSs effects differ between regions and types of intensive livestock farms. Although sows cause more PM released than fattened pig, PM released per fattener place is higher considering fattened pigs number per animal place per annum (3 pigs). Therefore, the reduction of PM emission is more efficient at farms with high number of fattened pigs' places. Minimal discrepancies in PM and NH_3 emission reduction occurs for different filter types and results from the adjustment of optimal modelling solution to scenario assumptions. Also the variation in average costs for PM and NH_3 emissions abatement vary between EATS types. The cheapest mitigation of both PM and NH_3 results from the installation of 1-stage chemical scrubber in all study regions. With shifting of PM and NH_3 reduction rates from minimal to maximal values average emission abatement costs decrease by slightly more than 30% for PM_{10} and NH_3. Keeping filter wastewater in separate storage confinement instead of adding it directly to slurry storage tank causes the increase of average costs for PM and NH_3 emission reduction by up to 50%.

7.7 Combination Scenario (Scenario VIII)

In the framework of all above described *scenarios* emission mitigation strategies are checked for their environmental and economic efficiencies. The analysis is carried out under assumption of ceteris paribus situation for all factors except subjects of particular *scenarios*.

Initially average abatement costs have serves as a determinative factor for *scenarios*' efficiency. However, implementation of several emission mitigation options resulting in financial surplus for farmers may come up with low emission abatement, e.g., CP-limited pigs feeding, but major costly abatement measures lead to a relatively high emission reduction. Moreover, if average abatement costs are a sufficient criterion for efficiency assessment from farmer perspective, this approach seems to be limited at the regional level. Nevertheless, to work out the efficient emission abatement strategy it is important to combine emission reduction options meeting expectations of both farmers and policy makers. For this sake, avoided damage costs are calculated with a special model elaborated at IER, University of Stuttgart, and provided for this study in the framework of the DFG-project. It is done to estimate pollutants' harmful effect for the overall economy. Computed for each farm type avoided damage costs in comparison with mitigation costs and resulting net benefits are presented in Table 50. Net benefits or monetarised externalities, in turn, result from the distraction of absolute change in gross margin (abatement costs) from avoided costs of damage. Net benefits give a better understanding of emission mitigation option's effect on health and terrestrial biodiversities (WAGNER *et al.*).

Scenario VIII aims to find relatively more efficient abatement measures in order to combine them together in a framework of the best mitigation scheme. The uppermost net benefit is the selection criterion for each individual emission reduction option.

Table 50 The comparison between abatement costs and reduced costs of damage and net benefit (EUR ($\times 10^6$)) resulting from different scenarios in Baden-Württemberg, Lower Saxony, and Brandenburg

Scenario		BW			LS			BB		
		Mitigation costs	Avoided damage costs	Net benefit	Mitigation costs	Avoided damage costs	Net benefit	Mitigation costs	Avoided damage costs	Net benefit
I		96.3	98.8	2.5	27.4	264	237	15.7	141	126
II		43.7	37.7	-6.0	109	158	49.1	29.5	25.5	-4.0
III	Sows	-6.6	7.7	14.3	-22.3	26.3	48.6	-4.9	4.9	9.8
	Fattened pigs	-4.0	1.7	5.7	-22.9	-18.3	4.6	-1.6	0.2	1.8
	Broilers	1.7	0.3	-1.4	55.8	44.0	-11.8	5.2	2.9	-2.3
	Laying hens	9.9	19.3	9.4	49.5	87.0	37.5	9.2	19.1	9.9
IV	Granulate	3.8	43.5	39.7	14.5	166	152	3.9	17.8	13.9
	Foil	16.1	47.4	31.3	34.8	185	150	5.9	17.3	11.4
	Hexa-Cover	7.4	35.8	28.4	21.2	143	122	3.1	17.8	14.7
	Tent roof	16.1	46.8	30.7	35.7	187	151	7.4	20.2	12.8
	Concrete	13.6	46.8	33.2	32.1	152	120	15.3	20.2	4.9
	V.a. concrete	14.7	40.1	25.4	34.7	217	182	--	--	--
V	Trailing shoe	35.8	94.1	58.3	78.3	264	186	12.5	37.2	24.7
	Injector	39.9	109	69.1	87.0	295	208	14.2	42.1	27.9
VI		-63.4	68.4	132	-252	34.9	287	-28.1	64.9	93.0
VII	Biofilter	26.5	36.0	9.5	29.3	173	144	6.0	9.1	3.1
	Trickle bed reactor	53.2	86.9	33.7	174	391	217	9.1	33.2	24.1
	1-stage chemical scrubber	32.9	91.5	58.6	98.2	417	319	7.1	33.5	26.4
	2-stage scrubber	58.0	76.5	18.5	188	373	185	9.7	33.1	23.4
	3-stage filter[1)]	55.7	97.3	41.6	174	408	234	8.5	33.5	25.0
	3-stage filter[2)]	56.1	93.2	37.1	178	330	152	9.2	33.5	24.3

Notes: I – Abdication of urea in mineral fertilizers; II –Switch for the solid manure based animal husbandry system; III – CP-low fodder; IV – Covering of manure storage; V – Manure land application; VI – Reduced tillage; VII – Exhaust air treatment; [1)] 3 stage EATS with bio, chemical and water cleaning stages; [2)] 3-stage EATS with 1 chemical stage and 2 water stages

A negative sign of mitigation costs tells about positive financial outputs resulted from the implementation of abatement measure. If the avoided damage costs are negative, then emissions cause higher damage than in BAU. Measures with negative net benefits are economically inefficient. Hence, only abatement options with positive and higher net benefit are joined together in the course of abatement strategy's suggestion and the **Scenario VIII** calculation. No subventions in a framework of regional environmental programs are considered for this *scenario* (section 3.1.3). The scenario results in comparison to respective BAU outputs for Baden-Württemberg, Lower Saxony, and Brandenburg are presented in Table 51.

The scenarios with the highest net benefit differ between farms, administrative regions, and federal states (Tables 50, 51). Thus, it cannot be stated that the vehicle access concrete cover is most efficient measure for NH_3 emission reduction for all regions and farms of Lower Saxony. However, at this stage of work presentation of the results for federal states rather than for farms and administrative regions is reasonable, as implementation of an elaborated mitigation scheme can mainly be afforded at a higher administrative level.

Table 51 Results of the combination scenario (**VIII**), for study regions

	Units	BW	LS	BB
Scenario results				
Gross margin	EUR ha^{-1}	1,291	1,642	895
PM_{10} total	kg ($\times 10^{-3}$)	7,753	18,629	6,388
$PM_{2.5}$ total	kg ($\times 10^{-3}$)	2,151	5,062	1,841
NH_3 total	kg ($\times 10^{-3}$)	24,881	47,221	11,002
GHG total	kg ($\times 10^{-3}$)	4,877,079	10,725,494	4,320,436
Changes to the reference				
Gross margin	EUR ($\times 10^{-3}$)	-45,119	-98,785	-37,708
PM_{10} total	%	-29.3	-40.1	-50.4
$PM_{2.5}$ total	%	-20.5	-33.7	-37.6
NH_3 total	%	-20.4	-46.3	-47.2
N_2O	%	-6.4	-9.5	-15.7
CH_4	%	-18.8	-6.9	-5.5
CO_2	%	20.0	-4.5	-11.9
GHG	%	-23.6	-29.6	-20.2
Average abatement costs				
PM_{10} total	EUR/kg PM_{10}	9.5	7.9	5.8
$PM_{2.5}$ total	EUR/kg $PM_{2.5}$	53.5	38.4	34.0
NH_3 total	EUR/kg NH_3-N	3.8	2.4	3.8
GHG total	EUR/kg CO_2e	0.3	0.0	0.0

Notes: BW – Baden-Württemberg, LS – Lower Saxony, BB – Brandenburg

Due to the **Scenario VIII** calculations, the decrease in gross margin is the lowest in Lower Saxony (slightly over 2%) and the uppermost in Baden-Württemberg (more than 21%). Brandenburg takes a middle position with 3% of gross margin reduction.

Total PM losses in Brandenburg decrease by nearly 50% for PM_{10} and 37% for $PM_{2.5}$. This is the highest reduction ratio comparing to Baden-Württemberg (ca. 29% and 21% for PM_{10} and $PM_{2.5}$, respectively) and Lower Saxony (about 40% for PM_{10} and 34% for $PM_{2.5}$). Ammonia emissions decline with the uppermost ratio in Brandenburg (47%) and Lower Saxony (46%). Controversially to the development of other pollutants, GHG losses drop by the highest rate in Lower Saxony (ca. 30%), comparing to Baden-Württemberg (24%) and Brandenburg (20%).

The average abatement costs are higher for Baden-Württemberg, due to a relatively moderate emission reduction. There is a discrepancy between average costs of PM and NH_3 abatement in Lower Saxony and Brandenburg. It reflects the prevailing character of agricultural production in these regions: higher livestock density in Lower Saxony results in a less costly NH_3

abatement, while intensive arable production allow the highest reduction in PM losses stemming from arable land in Brandenburg.

Figure 22 provides a basic insight into the contribution of administrative regions to the total emissions in Lower Saxony and Baden-Württemberg.

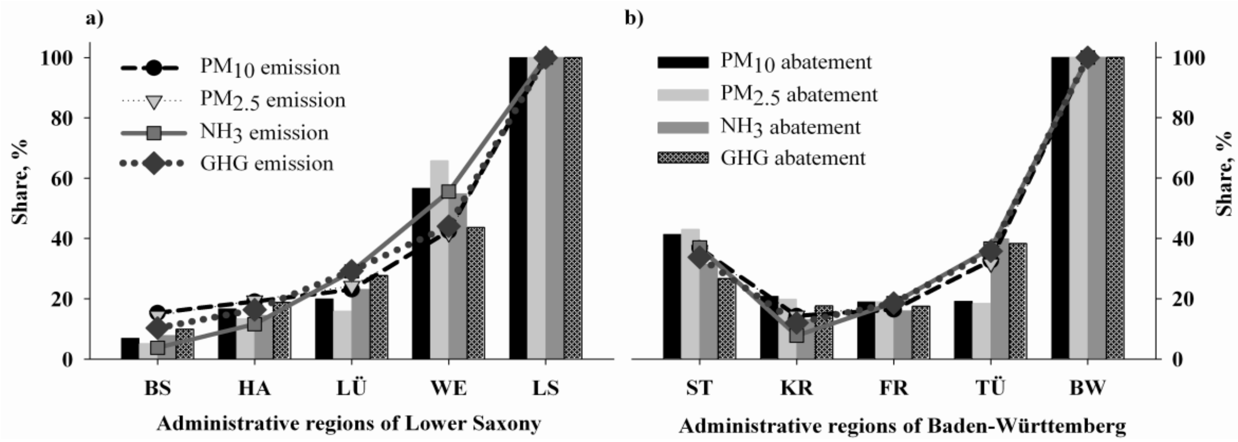


Figure 22 Shares of the administrative region in total emissions and their abatement in Lower Saxony (a) and Baden-Württemberg (b) due to the introduction of **Scenario VIII.**

Notes: BS – Braunschweig, HA – Hannover, LÜ – Lüneburg, WE – Weser-Ems, LS – Lower Saxony, ST – Stuttgart, KR – Karlsruhe, FR – Freiburg, TÜ – Tübingen, BW – Baden-Württemberg

Where bars of abatement overcome the lines of emissions, there the regarded combination of mitigation options is more efficient. The most efficient emission reduction in Lower Saxony is detected for Weser-Ems, where livestock density is the highest (1.4 LU ha^{-1}). Moreover, in Weser-Ems PM abatement resulting from the *scenario* is efficient, as the regional contribution to the overall PM cut off (57% and 66% for PM_{10} and $PM_{2.5}$, respectively) prevails over share of the administrative region in total PM emissions (42% for PM_{10} and 43% for $PM_{2.5}$). The contribution to the total PM losses is threefold higher for Braunschweig, comparing to the regional share in PM emission reduction, therefore, abatement results cannot be regarded as efficient there. Following the above mentioned criterion, mitigation of NH_3 and GHG is less efficient for Weser-Ems and Lüneburg, while GHG emissions reduction is efficient only in Hannover (Figure 22a).

In Baden-Württemberg PM emission reduction is the most efficient for Stuttgart, as its share in PM emission abatement (ca. 42% for both PM fractions) is higher than contribution to the total PM losses. However, NH_3 and GHG emissions reduction is the least efficient in this administrative region, as its share in overall pollution in Baden-Württemberg is ca. 7% higher than its contribution into NH_3 and GHG emission reduction in this federal state. The least efficient PM emission abatement occurs in Tübingen, due to 13% higher contribution to federal state's overall PM released than to the cut off in PM losses. Karlsruhe contributes less to the total PM and NH_3 emissions in Baden-Württemberg, i.e., by 14% and 8%, respectively, than other administrative regions. There 5-6% higher share in PM and NH_3 emissions abatement and lower input to overall pollution in Baden-Württemberg speak for efficient abatement of these pollutants.

Costs of damage for national economics as well as net benefits from **Scenarios VIII** implementation are presented in Table 52.

Table 52 Mitigation costs, avoided costs of damage, and net benefits (in EUR ($\times 10^6$)) resulting from the combination scenario **(Scenario VIII)** implementation in study regions

	BS	HA	LÜ	WE	LS	ST	KR	FR	TÜ	BW	BB
Mitigation costs	4.6	-9.9	-56.1	160	99.0	20.1	-3.3	3.9	24.4	45.1	37.7
Avoided damage costs	82.1	162	245	489	1,107	136	67.6	58.2	121	353	327
Net benefits	77.5	172	301	329	1,008	116	70.9	54.3	96.6	306	289

Notes: BS – Braunschweig, HA – Hannover, LÜ – Lüneburg, WE – Weser-Ems, LS – Lower Saxony, ST – Stuttgart, KR – Karlsruhe, FR – Freiburg, TÜ – Tübingen, BW – Baden-Württemberg, BB – Brandenburg

The net benefits in Table 52 are comparatively higher for Lower Saxony and its administrative region Weser-Ems, i.e., 1,008 and 329 EUR ($\times 10^6$), correspondingly.

In general, in this section it is shown that the combination of different abatement measures may lead to the reduction of NH_3 losses in the year 2015 by ca. 50%, depending on the region. Abatement of up to 50% and 40% can be expected for PM_{10} and $PM_{2.5}$ emissions. Moreover, GHG, which long term damaging effect on the environment is very high, decrease by nearly 30% after combining of the most efficient abatement measures.

8 DISCUSSION

This study determines PM, NH_3, and GHG emissions and their development at the farm and regional level due to the changes in overall political, economic and environmental circumstances. Linear programming economic-ecological farm emission model (EFEM) is chosen as a methodological approach for scenarios calculation. At the first place the results for reference scenario (for the year 2003) and its projection for 2015 (BAU) are summarized. Further, outcomes from the employment of different emission abatement instruments, i.e., exclusion of urea from mineral fertilization practise and reduced tillage, CP-low animals' feeding, environmentally friendly manure storage and land application, and treatment of EA in pigs' houses, are analysed in comparison with the modelled BAU outputs. The last section starts with the discussion of the uncertainty and its various aspects and continues with political strategy for emission reduction suggested based on the modelling outcomes.

8.1 Uncertainties

A necessary condition for accurate emission calculations with EFEM is the quality of basic information, i.e., emission factors, activities, and census data. However, uncertainties occur in structured way and it is important to understand their reasons.

The first type of uncertainty, which has been faced during this study, is the shortage of scientific explanation due to the lack of measurements. Thus, there are not enough data on PM emission intensities, e.g., for harvesting of various crops, tilling of different soil types and employment of special land preparation techniques, i.e., harrowing, discing and soil preparation for sowing or planting. Moreover, the science of measuring emissions from construction and industrial sectors, household activities (like fireworks, grilling, and cigarettes' smokes) and agriculture is still at its early development stage. For improving the situation it is crucial to take more measurements of PM emissions during different seasons (UIHLEIN *et al.*, 2003), for various soil types (in case of tillage operations and sometimes harvesting), for both PM_{10} and $PM_{2.5}$, and for as many crops and animal types as possible. Resulting wide data range will allow assessment of emission factors with lower uncertainty rate. In addition, uncertainty related to the quality of taken measurements has to be minimized. For instance, measurements of PM losses must be taken for whole 24-hours period (especially relevant for measuring PM in animal barns) (HEYLAND *et al.*, 2006).

In the case of NH_3 emissions, both variations between emission rates and choice of emission calculation method are responsible for uncertain estimates. Nevertheless, not all of them can be explained by physical and chemical processes. Errors in estimation of NH_3 losses may result from the sampling, i.e., definition of N-content (KOERKAMP *et al.*, 1998). Moreover, considering instability of gases under varying ambient conditions, it can be said that even very precise NH_3 concentration measurements can hardly be interpolated to the higher scale (e.g., regional) avoiding uncertainty. According to AMON *et al.* (2001), NICHOLSON *et al.* (2004), and KOERKAMP *et al.* (1998), the error in estimation of NH_3 emission rates tends to be minimal (less than 30%) for determination of NH_3 factors from the topmost practised activities, i.e., manure management in livestock houses, manure storage and land application. Lacking attention of such sub-categories of manure management as storage of slurry and solid manure, grazing and intensive poultry management can cause uncertainty level of over 30%.

There are some uncertainties, which arise from assumptions and simplifications. In this study based on the modelling procedure, making assumptions and approximations is essential, and related uncertainties have to be taken into account. For instance, the assumption that 100% of fattened pigs are housed in barns with liquid manure systems is rough, for about 17-20% of animals of this type are held on the deep litter.

As PM emission factors are not available for each crop type in EFEM, some relevant assumptions and approximations are performed. The assumptions on shares of $PM_{10}/_{2.5}$ in TSP taken from UIHLEIN *et al.* (2003) may lead to uncertain results, particularly if PM_{10} and $PM_{2.5}$ are hardly correlated.

Unavailability of time series for emission factors for both PM and NH_3 is another issue causing uncertainty for the future projection of emissions. The measurements of emission intensities are either few, like in the case of the PM losses, or are too general and independent on the measurement year. For instance, more measurements of PM emission rates at different conditions (i.e., weather and soil conditions, soil type, depth of the tillage, etc.) are necessary for better analysis of the reduced tillage effect on PM released. Otherwise, PM losses are the same for dissimilar study regions, where, in the reality, amount of PM released alters in a certain range depending on the above-mentioned circumstances.

Activities data, both from the statistical institutions and forecasted, imply significant uncertainty. Thus, incompleteness of collected data, e.g., FADN, and thereafter, arisen difficulties with the true situation description is a reason for uncertainties. In this study, this draw back is eliminated through the application of the extrapolation procedure.

Emission development in medium and long term depends on economy structural changes, population growth, changes in global domestic product (GDP), technological progress, and the legislation. However, the fact that EFEM is a static partial equilibrium model does not allow taking into account the major of above-mentioned dynamics. This, in turn, causes uncertainties, which are especially important to consider for the model projection demonstrating emissions development in medium and long term.

Very few information sources provide uncertainty estimates. However, to quantify uncertainties it is important to compare results of sensitivity analysis with outcomes of the alternative modelled scenarios. But systematic quantification of uncertainties and caring out of sensitivity analyses is very complex. By this reason after consideration of the development of European air quality policy, it makes sense to introduce the national emission thresholds for pollutants and to compare, how close are prognoses of different models to the established ceiling values (JÖRß *et al.*, 2007). This task gets complicated on the background of limited number of models similar in approach, character, covering the same levels of modelling, i.e., the farm, regional, and country level, and analysing the same mitigation strategies. However, average abatement costs resulting from the implementation of several emission reduction options are compared between EFEM, GAS-EM, and RAINS) for order of magnitude. The comparison reveals positive results.

8.2 Future Development and Policy Advise

In the period from 1995 to 2003 number of small farms decreased by about 26%, while amount of big farms raised by ca. 17%. Moreover, intensive structural changes in agriculture, in favour of large farms are expected to the year 2015. These variations together with prevailing over time intensive character of agricultural business may speak for higher impact on the environment, i.e., due to oversupply of nutrients to agricultural soils and higher emissions from livestock management. Moreover, requirements to environmental and animal protection and job safety standards get stricter. Orientation of livestock production toward animal welfare means, for instance, changes from slurry based housing systems to deep litter systems; the latter results in higher PM emissions from animal husbandry. This, in turn, requires improvement of already known abatement measures (GRIMM *et al.*, 2005; FREDE, 2005).

To introduce a consistent environmental policy it is not enough to make political decisions based only on the feelings of the reality. There are also must be the understanding of possible and necessary. It is hard to meet combination of these abilities by politicians and agricultural producers. As politics is the point of compromise between policy makers and farmers, their collaboration is crucial (SCHULZ, 2005; DRALLE, 2005). To assure it, existing and proposed political instruments supporting emissions abatement must meet several criteria. The first one is *enforceability* implies an existence of obstacles like conflict of interests. For instance, politicians expect positive long term returns from the implementation of policy measures, their contribution to sustainable development and synergy between different spheres of national economy. However, these interests of politicians may conflict with interest of farmers, aiming to build own capital from sufficient returns of production factors mainly in short and medium terms. Other sub-targets, such as keeping of sustainable agricultural business for the next generations and carrying out of environmental protective activities, are conditioned by the above-mentioned monetary target. Still the interests of policy makers and farmers may be two links of the same chain. Low interest to emission abatement from the side of agricultural producers may result from the fact that very few farmers know about contribution of agriculture to the atmospheric pollution, believing that the major emissions stem from industry and traffic. The lack of necessary knowledge on agricultural practise and its environmental aspects by policy makers is counterbalanced with higher interest to socioeconomic and cultural issues, which face agriculture in industrial countries, i.e., trade liberalization, food quality and safety, animal welfare, and rural development. Addressing their objectives, farmers choose proper management, but each farmer has an individual perception of organization with following unique combination of various emission sources. This is an additional obstacle on the way for correct political decision making about environmental issues (DÄMMGEN *et al.*, 2004; DÖHLER *et al.*, 2002; OENEMA *et al.*, 2004).

All emission abatement options are eventually bound with costs. Hence, their *financial efficiency* is the second crucial evaluation criterion. In general, only relatively less costly emission abatement techniques can be considered as plausible by the farmer (BUSSINK *et al.*, 1998). Nevertheless, high *mitigation potential* of the emission abatement measures can be the reason to accept relatively costly measures. The emission abatement is higher if the reduction measure is implemented at the production stage rather than retailers and processors. However, in this case the transaction costs are comparatively higher, as more actors involved in the emission reduction procedure (CLEVELAND *et al.*, 2002; OENEMA *et al.*, 2004). The heterogeneity of *average abatement costs*, caused by variability of emission intensities, farming activities, and their substitutability, plays important role in the selection of an optimal mitigation policy. Here environmental efficiency of emission reduction options has to be considered in the combination with their effect for the total economy. In this sense average abatement costs do give only narrow picture on the overall effect of individual measures. Therefore, *net bene-*

fit, calculated as the difference between avoided costs of damage and mitigation costs, was analysed, as it compiles positive and negative effects of all emissions for the whole economy.

The technical character of mitigating options explains *feasibility* and *controllability*. The emission reductions measures have to be plausible for single farms in order to be accepted, but they must meet political targets at the same time. Both political objectives and acceptability by farmers greatly depend on the regional specifics (DÖHLER *et al.*, 2002; OENEMA *et al.*, 2004). In order to bring both points of view together in a structural way, it is necessary to provide extension services for farmers (indirect environmental instrument) and proper stimulating and rewarding and at the same time forbidding and penalizing environmental regulation (direct environmental instrument). These instruments intend to make the polluter to face economic results of non-environmentally friendly action vices (OENEMA *et al.*, 2004; DÖHLER *et al.*, 2002). This study has suggested different farming options followed with the reduction of certain emissions. This positive result could already be achieved through the organisation of education and extension services for farmers.

In general, all interventions related to the emission abatement can be subdivided into mild, moderate, and severe (CHADWICK *et al.*, 2004). The PM and/or NH_3 abatement scenarios presented in this study can be differentiated only for two types of interventions, i.e., mild and moderate. Introduction of CP-low fodder for animals, changing livestock management systems, exclusion of urea from mineral fertilization practises, techniques for manure storage and land application and introduction of reduced tillage to agricultural land belong to *mild interventions*. Use of additives for animal feeding or stored manure, employment of new techniques for EA treatment can be classified as *moderate interventions*. *Severe interventions* imply the impact on the source of emission through, e.g., reduction of livestock heads, closing polluting farms, taking off higher acreage of arable land for fallow practises. Severe interventions are results of decision making at the policy level and the task of this study is to avoid them throughout provision of necessary information and suggestions on mild and moderate interventions to assure economic and environmental conditions, which are more favourable for our society.

The first abetment option analyzed in this study is the **exclusion of urea from the mineral fertilization practises**. It is relatively costly measure, as it presumes exclusion of fertilizer with comparatively lower costs for each kilogram of N, but followed with a considerable NH_3 reduction. Resulted average abatement costs differ among farm categories, but in acceptable for farmer range. The way to carry out this abatement technique is not complicated, as it just requires changes of the farmers purchase preferences. From the politicians' perspective this option is efficient and applicable in major regions, as the resulting net benefit is positive and high for some regions, i.e., 237 EUR ($\times 10^6$) in Lower Saxony and 126 EUR ($\times 10^6$) in Brandenburg. Farmers can accept this practise voluntary after introduction of some extension services. However, there are always agricultural producers, who are against extra expenses for something not related to direct short term returns. In this case, urea price can be additionally increased so that the price of per 1 kg urea-N will be higher comparing to more environmentally friendly fertilizers. Alternatively, introduction of taxes for urea application may push farmers to conduct more environmentally friendly fertilizing practises. Establishment of the manure exchange in all regions is very important, as it assures availability of organic alternative to mineral fertilization.

Changing from slurry to solid manure based livestock management system is undoubtedly efficient measure for NH_3 emission abatement, but its reduction potential directly depends on the number of livestock at farms, where this option is implemented. Mitigation of NH_3 losses from solid manure production can be very small or even negative due to its emission intensive storage and treatment of leachate. In addition, a higher straw amount applied and long term keeping of manure in animal house lead to relatively high NH_3 emissions. Also problem related to high long term NH_3 losses from the solid manure spread onto the field arises. Moreover, precipitation does not cause the same positive effect on NH_3 emission reduction from solid manure as from slurry land application. Immediate incorporation of solid manure into the soil after spreading, if possible, assures minimization of NH_3 losses by up to 100%, but may result in boos of PM and GHG emissions. Environmental problems caused by solid manure land application have different effect on farms with different production specifics, e.g., grassland and arable farms. Thus, for arable farming and extensive forage growing a certain amount of solid manure is advantageous. However, environmentally friendly application of organic manure by intensive grass production at forage growing farms is only possible with slurry based manure system. Solid manure, with its high share of organically bounded N, does not provide enough N to the grass in definite intervals and cause not only high NH_3 losses, but also high NO_x emissions (OTT, 1990; DÖHLER, 1990). Changing of slurry based animal housing system in favour of solid manure based system may cause a negative development of the PM emission from animal house, as for some animal categories (i.e., male cattle, and heifers) housing on solid manure is associated with higher amount of PM released.

From the point of feasibility, the introduction of new system is related to additional costs for a bedding material and labour for its regular renewal. Total costs vary depending on the fact, whether the solid manure system is introduced in a newly constructed building (as it has been assumed in this study) or it is established in the house with slurry based livestock management system. The latter implies additional expenses, which in turn alter based on the type of adjustment in animal barn (e.g., installation of a new system for manure floor-scrubbing and adjustment of barn floor). Due to possible discrepancies in scenario results for various farms the same measure will hardly be acceptable for all farm categories. Moreover, summed emission effects and financial results turned out into negative net benefit in Baden-Württemberg and Brandenburg. This speaks for unacceptability of the switch from slurry to solid manure based livestock hosing system for the overall economy.

Analysis of NH_3 emission reduction measure such as **feeding of pigs and poultry with CP-limited fodder** reveals more or less homogeneous emission reduction among animals by very negligible rate, namely up to 2%. Although the absolute decrease in excreta-N content varies from 4.1% to 25%. This idea is in contradiction with the several studies' statements, e.g., POWERS *et al.* (2007), DEFRA (2002), UNECE (2007) and HAYES *et al.* (2004b), that the adjustment of CP-level in livestock diet assures reduction of N excreted by 30-45% and hence significant abatement of total NH_3 losses. For instance, according to HAYES *et al.* (2004b), 40% less CP in animal ration may result in NH_3 emission abatement by 60%. This discrepancy can be justified by the specifics of EFEM-approach for the calculation of N-emissions, where all manure management stages and multiple sources of NH_3 losses are taken into account. By this reason reduction ratio for N in livestock excreta is not significant on the background of the cumulative NH_3 emissions stemming from several manure management stages.

The side effect of the NH_3 abatement option on PM and GHG differs between regions and farm types. The costs from this abatement option implementation vary between livestock categories. Thus, if introduction of CP-low feeding strategy by pigs in all regions is bound with profit, such dietary practise for poultry, especially broilers, is generally costly. Costs of CP-adjusted diets include expenses for facilities, labour, special food additives, and relevant knowledge. Not every farmer can afford implementation of CP-low feeding of livestock; therefore, the decision about feeding livestock with CP-low diet is to be taken individually for each region and even farm. However, positive net benefit results from introduction of CP-adjusted diet by sows (14.4, 48.6, and 9.8 EUR ($\times 10^6$) for Baden-Württemberg, Lower Saxony, and Brandenburg, respectively) and fattened pigs (5.7, 4.7, and 1.8 EUR ($\times 10^6$) for Baden-Württemberg, Lower Saxony, and Brandenburg, correspondingly), and negative net benefit by poultry, with some exceptions for laying hens. In general, this measure is much less efficient than above regarded NH_3 abatement options. Introduction of taxes for each exceeding kg of N in animal excreta or quota for the respective N-content will only boost the costs of CP-limited feeding practise, but not improve its emission reduction efficiency. Moreover, expenses for control are expected to raise, that put introduction of CP-reduced diets beyond borders of financial efficiency. Under this consideration, additional measures related to animal feeding and leading to NH_3 and/or PM emission reduction are to be implemented together with CP-low feeding. For instance, different additives can be introduced into animal fodder. However, more investigations are required in this field.

Taking into the account the efficiency of different measures making manure management more environmentally friendly, their affordability for farmers has to be taken into account. At first place, farm size, production emphasis, and amount of agricultural land determine choice of matching type of slurry storage cover and manure land application technique. At second place, the financial aid to the farmers is the additional motivational factor for conducting of these environment oriented agricultural practises. **Manure storage** cover is efficient, but costly measure for NH_3 abatement. The highest net benefit results from the manure storage cover with granulate (39.7 EUR ($\times 10^6$)) in Baden-Württemberg, vehicle-access concrete cover in Lower Saxony (82 EUR ($\times 10^6$)) and Hexa-cover in Brandenburg (14.6 EUR ($\times 10^6$)).

Utilization of environmentally friendly techniques for **manure land application** requires following of basic rules in order to reach expected NH_3 emission reduction: manure is to be spread under relatively lower temperatures and preferably shortly before the rain (DÖHLER, 1990). Among different manure land application techniques, employment of injector technique is the efficient for all study regions (69.5, 208, and 27.9 EUR ($\times 10^6$) for Baden-Württemberg, Lower Saxony, and Brandenburg, respectively). Introduction of the premium for 1 m^3 of organic fertilizers applied to agricultural land with specific environment protecting techniques encourages farmers for production of slurry rather than more NH_3 emission intensive solid manure. Taxation of 1 m^3 of manure applied to the land with non-environmentally friendly techniques may be bound with the restricted control options. To improve the scenario effect and motivate farmers for introduction of environment friendly manure land application, premium can be provided for additional practises, such as diluting of solid manure and its further treatment. The financial aid then must at least cover additional expenses of water and other additives. Alternatively, the amount of solid manure applied onto the land can be taxed. The tax, in this case and generally, is higher than subvention, as it comprises the estimation of damage for overall economy. Another important measure, beside farmers' motivation, is the optimization of institutional net allowing agricultural producers, especially in livestock intensive regions, to sell the excess of farm manure. However, in case of manure storage cover and manure land application farmers do not need to be told, which type of emission abating technique has to be employed, as it is dictated by farm capacities, factor endowments, and regional conditions. For instance, introduction of immediate manure incorporation into the land or slurry application with injectors are not always possible, e.g., due to the existence of vegetation cover, or because of stony soils.

Although conservation agriculture, with its important aspect, i.e., **reduced tillage**, is often classified as an old fashioned agriculture (KERTÉSZ *et al.*, 2010), nowadays more and more farmers turn to this practise due to its environmentally friendly character. The main driving force for employment of reduced tillage is economic one. Current study reveals that application of reduced tillage is financially efficient. Moreover, due to this practise less amount of PM and GHG is released. The net benefit from reduced tillage employment is positive and high for all study regions (132, 287, and 93.0 EUR ($\times 10^6$) for Baden-Württemberg, Lower Saxony, and Brandenburg, correspondingly). However, several investigations demonstrate that reduced tillage practise may counteract with farmers expectation of high yield. The yield changes following the employment of reduced tillage depend not only on the tillage depth, but also on its endurance, soil type and quality (SILVA *et al.*, 2010). Thus, regional and farms specifics must be analysed before taking decision about applicability of the reduced tillage. This study shows that additional provision of subvention per hectare of arable land under conservation tillage increases this efficiency just slightly. Therefore, it can be substituted with investments in extension services for farmers.

With the extensive development of livestock husbandry, the distance between animal barns and residential area, biotopes, forests and recreational areas situated close to the dwelling zones progressively decrease. Due to the emissions stemming from animal houses, it becomes difficult to build a new or even to extend existing livestock facility. This has resulted in the political concern and future requirements to environmental protective character of the agricultural activities, particularly for livestock management, promise to be stricter. On this background more efficient measure for emissions reduction is found, i.e., **installation of filters**. Among different filter types analysed in this study the most efficient abatement of both PM and NH_3 losses and the highest net benefit result from the installation of 1-stage chemical scrubber (58.6, 319, and 26.4 EUR ($\times 10^6$)) in Baden-Württemberg, Lower Saxony, and Brandenburg, respectively).

Employment of filters has several obstacles. Firstly, EATS's installation and operation is expensive and therefore not affordable for all farmers. Its costs rise additionally for the installation in already build animal barn due to adjustments of building for filter mounting, introduction of extended slurry storage facilities or assuring separate storage of filter wastewater. Because of this EATSs do not belong to the state of art techniques. Hence, their installation is only reasonable, when territorial extension is not possible due to established place specific requirements (MELSE *et al.*, 2009b; DRALLE, 2005). All the above-mentioned aspects make this pollution abatement option unattractive for owners of relatively small livestock farms. Here, a further technological improvement of filters in order to reduce operational costs may assure wide application of EATS in the near future. This together with the fact that the knowledge on filters' abatement efficiencies is incomplete highlights the importance of support for a related research (JANSSEN *et al.*, 1990). It is important to mention that the total EATS costs do not depend on actual number of animal places, but rather on the filtering requirements for initial amount of animals in the barn by the filter installation. Hence, introduction of such coordinal measures as reduction of livestock number due to any reasons, e.g., overproduction, emission reduction, and changes in market contingent, parallel to EATS installation negatively affects economic efficiency of EA filtering due to relatively high operational costs per animal place.

Second obstacle on the way of widespread filter installation is the existence of uncertified EATSs, which do not guarantee proper mitigation of pollutants, on German market. The main reason for it is an optional character of the certified EATS. Considering this fact, it is important to motivate the producers of filters to certify their products. It is crucial to clarify that the certification is a further important step on the way to a high quality product and to progressive enterprise development.

Initially average abatement costs of different scenarios have been compared to the respective BAU results to define scenarios' financial efficiency in this study. As the environmental policy aims to reduce pollutants damaging effect in long and medium term and with a maximum positive effect for the overall economy, it implies the prevention of the shift into another environmental problem. Thus, tradeoffs and interlinkages between different emissions must be considered before suggestion and implementation of abatement strategy (DÖHLER *et al.*, 2002; DUXBURY, 1994; METHLING *et al.*, 2002). This is done in the framework of the scenarios' net benefits calculations, when mitigation costs and avoided damage costs for different emissions are considered. Net benefits for various scenarios are compared between each other and the ones with the uppermost net benefits have been combined together in the framework of the better abatement strategy (Scenario VIII).

To conclude about abatement efficiency of individual scenarios (Scenarios I – VII) and the better abatement scheme (Scenario VIII) at the country and federal state level, NH_3 and PM emission reductions resulted from the scenarios' implementation are compared with critical binding national reduction objectives repealing current National Emission Ceilings (NEC) values. These targets are set by the Directive of the European Parliament and of the Council on the reduction of national emissions of certain atmospheric pollutants and amending Directive 2003/35/EC. These new targets are based on NEC-principles, but they are presented as relative values to be met by 2020 and 2030 (section 3.2.5 and EUROPEAN COMISSION (2013).

The NEC-value for total NH_3 in Germany in 2020 constitutes 566 kt. According to the reports and prognoses of UBA (2009b, a), it cannot be reached under current policy for NH_3 emission reduction. An expected ratio for a total NH_3 emission reduction suggested by the European Commission in the framework of new directive equates to 5% per annum between 2020 and 2029 and 35% yearly starting from 2030 (BOURGUIGNON, 2015). As the major part of NH_3 released stems from agricultural sector, particularly animal husbandry and manure management (section 2.1.2.1), the assumption about the equivalence of the abatement value set for total NH_3 and ammonia stemming from agriculture has been made.

As it is determined in the Gothenburg Protocol, total $PM_{2.5}$ emission in Germany has to reach maximum 106 kt up to 2020. There are no NEC specified for PM_{10}, therefore, it is assumed that the abatement ratios of 26% between 2020 and 2029 and 43% starting from 2030 specified for $PM_{2.5}$ count also for PM_{10} (BOURGUIGNON, 2015). The same as for NH_3 it is assumed that major part of PM is emitted from agriculture. Of course, this assumption is very rough, as PM is emitted mainly by heating, industry and transport. This, however, have to be considered by following comparison of expected reductions up to the set NEC-values with scenarios individual abatement results.

Set emission reduction targets for annual emissions in Germany and estimated values for study regions, as well as shares of PM and NH_3 in German emissions and scenarios' abatement results compared to the BAU outputs are presented in Table 53. In the case of scenarios with various abatement alternatives, the one with the uppermost net benefit has been chosen for this analysis.

Table 53 Officially proposed reduction ratios for Germany and the best scenarios' abatement results modelled with EFEM

	BW	BB	LS	Germany
Annual emission reduction commitments for Germany, comparing to 2005, in %				
for PM_{10} between 2020 and 2029	-26.0	-26.0	-26.0	-26.0
for $PM_{2.5}$ between 2020 and 2029	-26.0	-26.0	-26.0	-26.0
for NH_3 between 2020 and 2029	-5.0	-5.0	-5.0	-5.0
for PM_{10} from 2030	-43.0	-43.0	-43.0	-43.0
for $PM_{2.5}$ from 2030	-43.0	-43.0	-43.0	-43.0
for NH_3 from 2030	-39.0	-39.0	-39.0	-39.0
Changes in PM_{10} emissions comparing to BAU, in %				
Scenario I	0.4	0.0	-0.1	--
Scenario II	3.8	-0.7	3.3	--
Scenario III	0.1	-5.2	-11.2	--
Scenario IV	0.0	0.0	0.0	--
Scenario V	0.0	-0.1	0.0	--
Scenario VI	-37.6	-43.1	-22.8	--
Scenario VII	-3.5	-1.2	-5.6	--
Scenario VIII	-43.5	-50.4	-40.1	--
Changes in $PM_{2.5}$ emissions comparing to BAU, in %				
Scenario I	0.1	-0.5	-0.1	
Scenario II	3.0	0.0	2.5	--
Scenario III	0.1	-8.8	-17.6	--
Scenario IV	-0.1	0.0	0.0	--
Scenario V	0.0	-0.1	0.0	--
Scenario VI	-22.0	-26.2	-12.1	--
Scenario VII	-1.8	-0.8	-3.0	--
Scenario VIII	-31.2	-37.6	-33.7	--
Changes in NH_3 emissions comparing to BAU, in %				
Scenario I	-13.3	-27.2	-14.8	--
Scenario II	-5.5	-5.2	-8.1	--
Scenario III	-2.3	-0.1	-1.2	--
Scenario IV	-6.8	-5.7	-7.5	--
Scenario V	-15.5	-12.7	-14.9	--
Scenario VI	1.6	1.2	0.3	--
Scenario VII	-12.7	-7.0	-19.5	--
Scenario VIII	-37.2	-47.2	-44.2	--

Notes: BW – Baden-Württemberg, LS – Lower Saxony, BB – Brandenburg, NEC – National Emission Ceilings; I – abdication of urea in mineral fertilizers; II – switch to the solid manure based animal husbandry system; III – CP-low fodder; IV – covering of manure storage; V – slurry land application; VI – reduced tillage; VII – exhaust air treatment, VIII – combination scenario

Sources: own calculations based on DÄMMGEN *et al.* (2009) and resulting from the EFEM modelling

The information in Table 53 has to be analysed in a following way: the different pollutant abatements are compared with the set targets for annual emission reduction for each study region and the whole Germany.

Thus, table shows that annual $PM_{10}/_{2.5}$ emission reductions expected form the employment of the reduced tillage (Scenario VI) in Lower Saxony is closer to the moderate annual estimated abatement targets between 2020 and 2029. In the same region, also PM emission reduction from introduction of CP-low diets by laying hens is closer to the target 2020-2029. Mitigation of PM losses resulting from the combination scenario (Scenario VIII) is overfulfilled in study regions for the reduction target 2020-2029 set by the European Commission for overall Germany. However, the modelled emission reduction of the most health relevant PM fraction with diameter 2.5 μm, which the target is primarily established for, is less efficient comparing to the proposed abatement value. Abatement of PM-losses resulting from the rest scenarios is even lower than a moderate annual reduction rate suggested for any year between 2020 and 2029.

Comparison of the emission abatement values proposed by the European Commission and EFEM outputs 2015 for NH_3-N losses reveals that with some exceptions the commitment for annual emission abatement for Germany 2020-2029 is much underestimated comparing to scenarios' mitigation outcomes. Differently looks the situation resulting from the comparison of the modelling outputs with the ambitious reduction target valid from 2030: only the result of the combination scenario is closer for Baden-Württemberg and overfulfilled for Brandenburg and Lower Saxony comparing to the set emission reduction targets (Table 53).

Following the results of Table 53 for both PM and NH_3 emissions, it can be said that application of several individual and combination scenarios may assured a promising emission reduction even overfulfilment of the commitments suggested by the European Commission in the proposed directive. However, in the case of such individual mitigation options, as the employment of the costly EATS (Scenario VII) for PM losses and introduction of CP-low fodder by pigs and poultry (Scenario III) for NH_3 emission reduction, abatement efficiency boost up is necessary. This has to be achieved under consideration of the fact that efficiency of each scenario varies from region to region. Therefore, local conditions have to be taken into account, while finding better policy measures for emissions abatement or improving existing ones. For this, regardless considerable achievements in emission abatement practises in agriculture and improved over time understanding of negative pollutants impacts on environment and human and livestock health, further research has to be conducted.

SUMMARY

Agricultural production comes along with numerous environmental effects, such as contribution to climate change, harmful to health emission impacts as well as eutrophication and acidification of soils and waters. Political regulations and environmental protection measures at the national and international level shall support development of sustainable agriculture. The intention of this work is to analyze the alterations of PM (particulate matter), NH_3 (ammonia), and GHG (greenhouse gas) losses from German agriculture arising due to adaptations in agricultural and environmental policy, and to find out efficient PM and NH_3 emission abatement options.

At the first place, the character of PM and NH_3 emissions from agriculture and the ways for their abatement are discussed. This production sector contributes approx. 95% to the overall NH_3 emissions. The respective estimates for PM_{10} and $PM_{2.5}$ are lower and reach only 9% and 7%, correspondingly; such low contribution of agriculture to an overall PM emission can be explained by the novelty of the topic and lack of measurements.

To show, how certain economic and political conditions and their adjustment over time do affect amount of NH_3, PM, and GHG released from agriculture and to evaluate emission mitigation options, economic-ecological static integer linear model, EFEM (Economic Farm Emission Model), has been developed. This model is based on bottom-up-approach, when the modelling results for individual farms can be projected to the regional level in the framework of the extrapolation procedure. Integrated into EFEM NH_3 and PM emission factors result from the extensive literature review and experts consulting, while the activities data stem from FADN (Farm Accountancy Data Network) and census databases. In EFEM farm structure, production activities and extrapolation tool are represented in the system of interrelated modules for five farm types, i.e., arable farms, forage-growing, mixed and intensive livestock farms (one with the emphasises on pig husbandry and another one specializing in poultry production). The modelling is done for three German counties and each of them has focus regions, which are exemplary for important sources of PM, NH_3, and GHG emissions in agriculture. Thus, following study regions have been chosen: Baden-Württemberg characterized by forage growing prevailing there, Lower Saxony marked by intensive livestock productions and Brandenburg due to its sandy arable sites at risk of erosion. Although this study is performed for Germany, its approach can be implemented for different countries, if secondary information database is complete.

At first, the model calculations are carried out for the year 2003, as the optimized reference situation, to define the emissions' status-quo. The next step is the modelling for the projection year 2015, as the BAU-scenario (business-as-usual scenario: updated frame conditions of agricultural policy), to demonstrate the emissions' development under certain economic and political conditions. The EFEM calculations for Lower Saxony for the year 2003 amount to ca. 34 kg NH_3-N/ha, 12 kg PM_{10}/ha, 3 kg $PM_{2.5}$/ha and 6,386 kg CO_2e/ha. These emissions are nearly 1.5-2 times higher than those once in Baden-Württemberg and Brandenburg. Validation of the reference outcomes for each study region through their comparison with figures of the German National Imission Inventory (NIR) discloses the overestimation of modelled PM and GHG emissions and underestimation of NH_3 losses. Such deviations can be explained by the following EFEM specifics: more disaggregated and process oriented modelling of the PM released from arable agriculture, additional reality relevant assumptions for NH_3 emissions calculation and differing aggregation of input census information. Comparing to the reference situation, the emission results for BAU 2015 are 4% to 20%, 2% to 10% and 2% to 20% higher for PM, NH_3, and total GHG, correspondingly. Lower Saxony demonstrates the uppermost absolute emissions increase: ammonia losses boost up from 81.0 million to 87.1 million kg NH_3-N (ca. +7.6%), particulate matter emissions from 27.1 million to 31.1 million kg for PM_{10} (+14.7%) and from 6.8 million to 7.6 million kg for $PM_{2.5}$ (+12.0%) and amount of GHG released from 15,033 million to 16,599 million kg CO_{2e} (+10.4%). However, in Brandenburg the relative emission alterations are the highest: with +9.4% (from 18.7 million to 20.4 million kg NH_3-N) for ammonia, +20.7% for PM_{10} and with +17.0% for $PM_{2.5}$ (from 10.7 million to 12.9 million kg PM_{10} and from 2.5 million to 2.9 million kg $PM_{2.5}$) for particulate matter, and +19.9% (from 4,687 million to 5,620 million kg CO_{2e}) for GHG. Nevertheless, in Baden-Württemberg the alterations for analyzed emissions are minimal, i.e., amounting to 0.5 million kg PM_{10} and 0.02 million kg $PM_{2.5}$ (+4.8 and +0.9%, respectively) for particulate matter, 0.6 million kg NH_3-N (+2.0%) for ammonia and 20.9 million kg CO_{2e} (+0.3%) for GHG. These figures demonstrate that changing frame conditions of the agricultural policy have the strongest negative effect for emissions in Brandenburg.

The efficiency of various NH_3 and PM abatement measures is determined through the comparison of scenarios' outputs with BAU results. The individual scenarios analyse the adjustments of emission sources in the framework of the emission relevant agricultural production practice, as exclusion of urea from mineral fertilization practices, switching from slurry to solid manure based livestock housing systems, introduction of crude protein (CP) reduced feeding by pigs and poultry production, environmentally friendly slurry storage and land application, reduced tillage, and installation of exhaust air treatment systems (EATS) in pig barns. Beside main scenario calculations for the CP-low feeding practices and mounting of exhaust air filters, the EFEM simulations have been carried out to observe the change in model behaviour for different values of some exogenous parameters.

Although the exclusion of urea from fertilization practice is easy to implement from the perspectives of both farmers and politicians, it is a relatively expensive NH_3 emission abatement measure especially for farms with relatively high livestock density. Thus, gross margin in Lower Saxony and Brandenburg decreases for mixed farms with 476 million EUR (-1.6%) and 576 million EUR (-1.8%), respectively, and for forage-growing farms with 1,722 million EUR and 182 million EUR (-0.3% in both regions), correspondingly. Beside the fact that the abdication of urea leads to a positive side effect for NO_2 and GHG emissions reduction, this option is bound with the highest, out of all abatement options analysed in this study, abatement of NH_3 released from mineral fertilization practices. The emission mitigation is particularly high for arable farms, where it reaches 89% (5.6 million kg NH_3-N in Lower Saxony, 2.8 million kg NH_3-N in Baden-Württemberg und 3.0 million kg NH_3-N in Brandenburg). The contribution of arable farms to the total regional reduction of NH_3 losses reaches nearly 50%. By the same reason, the average mitigation costs are the lowest for arable farms. At the county level greater land endowments of Lower Saxony speak for more efficient NH_3 reduction and lower average abatement costs, 2.4 EUR/ kg NH_3-N, than in other study regions.

The costs of the switch from liquid to solid manure based housing system for cattle depend on the adjustment to perform in the animal barn. The higher livestock density corresponds with the highest contribution to the total NH_3 abatement and the lowest average abatement costs. The switch from liquid to solid manure based housing system for cattle at farms and in regions with relatively high livestock density is followed with maximal NH_3 and GHG emissions reduction. However, this scenario implementation results in by up to 4% higher particulate matter emission. Among study regions, the average abatement costs of 15.3 EUR/ kg NH_3-N are lowest for Lower Saxony with a comparatively higher livestock density, i.e., 1.16 LU (livestock unit) per hectare.

Besides changing of housing system, there is a chance to reduce NH_3 losses from livestock barns via a gradual reduction of crude protein (CP) content in animal diet. Positive financial effect of this mitigation measure for pigs producing farms can be partially explained by the cutting off the amount of expensive high protein ingredients. At the farm level, livestock intensive farms with the emphasis on the sows breeding demonstrate the most positive NH_3

emission abatement scenario effect of up to 0.9 million kg NH_3-N (-6.7%) for Lower Saxony, 0.3 million kg NH_3-N (-6.6%) for Baden-Württemberg and 12.3 million kg NH_3-N (-7.8%) for Brandenburg. However, the uppermost NH_3 mitigation is negligible at the county level, i.e., 1.2 million kg NH_3-N (-1.5%) for broilers production in Lower Saxony, ca. 0.2 million kg NH_3-N (-0.8%) and 0.3 million kg NH_3-N (-2.4%) for breeding sows production in Brandenburg and Baden-Württemberg, correspondingly. These low reduction rates for both NH_3 and GHG losses can barely motivate farmers to implement this feeding system.

The employment of environmentally friendly techniques for manure storage covering and land application is common nowadays for the majority of German farmers. The techniques analysed in the study results in NH_3 emissions reduction improving from a cheaper to more expensive abatement option. In all study regions, livestock intensive farms with the emphasis on pig production and forage growing farms demonstrate the highest emission reduction due to a relatively higher livestock density. Comparing to other techniques injection of liquid manure into the soil and covering manure storage with granulate follows with a higher NH_3 abatement. Somewhat lower NH_3 emission reduction and more costly covering of slurry storage with granulate results in higher average abatement costs.

The area under conservation or reduced tillage in Germany as well as in EU is increasing. Modelling reveals that reduced tillage employment leads to less PM released from arable agriculture and results in financial surplus due to relatively lesser amount of diesel required for these practices. At the farm level, it is arable farms contributing the highest share of nearly 55% and 24% to the total PM reduction in Baden-Württemberg (-2.2 million kg $PM_{2.5}$ and -0.3 million kg PM_{10}) and Lower Saxony (-1.7 million kg PM_{10} and -0.2 million kg $PM_{2.5}$), respectively. Total GHG emissions decrease by up to 80% mainly due to CO_2 enclosure, i.e., with 15.2 billion kg CO_{2e} for Lower Saxony, 6.4 billion kg CO_{2e} for Baden-Württemberg und 5.4 billion kg CO_{2e} for Brandenburg.

Filters or Exhaust Air Treatment Systems (EATS) installation is costly, but efficient measure for the reduction of NH_3 and PM losses. Among multi-pollutant filters, installation of 1-stage chemical scrubber follows with a relatively cheap PM and NH_3 abatement. The sensitivity analysis demonstrates that the NH_3 emissions and average abatement costs are inversely correlated. Three levels of NH_3 emission factors, i.e., minimal, mean and maximal, are considered for this analysis. Modelling with the maximal value of the emission intensity results with up to 24% less NH_3 released in comparison to the IS-scenario. At the same time, average abatement costs are reduced by 30%. However, additional expenses for the building of separate storage for filter wastewater cause the increase of average abatement costs by 30% in contrast to the IS-situation, where it is assumed that the wastewater is stored together with slurry. At the farm level, PM emission reduction is the uppermost for livestock intensive farms with the emphasis on pig production, mainly due to higher amount of PM intensive breeding sows there.

Net benefit, as the difference between reduced costs of damage for human health and environment and mitigation costs, gives the insight into the effect of abatement measure for the overall economy. Among all scenarios analysed in this study, the emission abatement options assuring maximal net benefits and emissions reduction are combined together and suggested as the abatement strategy at the farm and policy level.

With the ratification of Gothenburg Protocol Germany commits to reduce emissions to the certain year up to the set National Emission Ceilling (NEC) values. The efficiency of any emission abatement measure is clear through the comparison of scenario results with national emission abatement ratios proposed by the European Commission for the years between 2020 and 2029. The efficiency of certain scenarios, however, varies for study regions due to their individual conditions.

Increasing attention to environmental problems at the regional and global level requires higher contribution of scientists from all over the world to the definition of pollution and emission abatement status. This study demonstrates the relevance of further investigation of PM and NH_3 emissions in and from agriculture and of the ways to abate them.

ZUSAMMENFASSUNG

Die landwirtschaftliche Produktion ist mit zahlreichen Umweltwirkungen verbunden, z.B. Beitrag zum Klimawandel, gesundheitsgefährdende Emissionsbelastungen sowie Eutrophierung und Versauerung von Böden und Gewässern. Gesetzliche Regelungen und Umweltschutzmaßnahmen auf nationaler und internationaler Ebene sollen eine nachhaltige Landwirtschaft fördern. Ziel der vorliegenden Arbeit ist es, die Änderung der Belastungen durch Feinstaub (PM)[40] , Ammoniak (NH_3) und Treibhausgas (THG)-Emissionen aus der Landwirtschaft in Deutschland bei veränderter Landwirtschafts- und Umweltpolitik zu analysieren und darauf basierend effiziente Vermeidungsoptionen für die Feinstaub- und Ammoniakemissionen abzuleiten.

Zu Beginn werden die Feinstaub- und NH_3-Belastungen aus der Landwirtschaft und deren Vermeidungsmöglichkeiten erläutert. Allein der Anteil der Landwirtschaft beträgt bei den gesamten NH_3-Emissionen rund 95%. Die entsprechenden Schätzwerte für PM_{10} und $PM_{2.5}$ betragen 9% bzw. 7%. Allerdings können diese Feinstaubwerte aus der Landwirtschaft bisher nur ungenau kalkuliert werden, was an der Neuigkeit des Themas sowie an mangelnden Messwerten liegt.

Um aufzuzeigen, inwiefern wirtschaftliche und politische Rahmenbedingungen und deren Anpassungen im Laufe der Zeit die emittierten Mengen von Feinstaub, NH_3, und THG aus der Landwirtschaft und deren Vermeidungsoptionen beeinflussen, wurde das statische, ökonomisch-ökologische Integer-lineare Modell EFEM (Economic Farm Emission Model) angewandt und für die spezifischen Fragestellungen weiterentwickelt und angepasst. Es ist ein Bottom-Up-Modell, das auf Basis von einzelbetrieblichen Modellen, Regionen mit Hilfe von Hochrechnungsfaktoren abbilden kann. Emissionsfaktoren für Feinstaub und NH_3 wurden durch umfangreiche Literaturrecherche und Expertenbefragungen ermittelt, während die landwirtschaftlichen Produktionsdaten aus der INLB (InformationsNetz Landwirtschaftlicher Buchführungen)-Datenbank und der Landwirtschaftszählung stammen. EFEM ist modular aufgebaut und verfügt über ein Betriebsstruktur-, ein Produktionsverfahrens- und Hochrechnungsmodul. Für diese Studie werden fünf verschiedene Betriebstypen: Ackerbau-, Futterbau-, Gemischt- und Veredlungsbetriebe (jeweils Schweine- und Geflügelproduktion) abgebildet. Die Modellierung wird für drei deutsche Bundesländer durchgeführt. Jedes dieser Bundesländer hat Schwerpunktregionen, die für wichtige landwirtschaftliche Quellen von Feinstaub-, NH_3- und THG-Emissionen beispielhaft sind. Untersucht werden Baden-

[40] PM_{10} und $PM_{2.5}$ (Engl. particulate matter) stehen für Feinstaub mit aerodynamischem Durchmesser von 10 bzw. 2.5 Mikrometer.

Württemberg, das durch intensive Futterbauregionen gekennzeichnet ist, weiterhin Niedersachsen, geprägt durch intensive Veredlungsstandorte und Brandenburg, aufgrund sandigen und damit erosionsgefährdeten Ackerbaustandorten. Obwohl die vorliegende Arbeit sich ausschließlich mit Deutschland befasst, kann das Modell auch für andere Länder eingesetzt werden, sofern eine vollständige Datenbank mit den relevanten Sekundärdaten verfügbar ist.

In einem ersten Schritt wurde eine Referenzsituation für das Jahr 2003 modelliert, um den Emissionen-Status-quo zu definieren. In einem weiteren Schritt wurden für das Jahr 2015, als BAU-Szenario (Business as usual: aktualisierte agrarpolitische Rahmenbedingungen), Berechnungen mit EFEM durchgeführt, um die Emissionsentwicklung bei bestimmten ökonomischen und politischen Rahmenbedingungen darzustellen. Die mit EFEM berechneten Emissionen für das Jahr 2003 belaufen sich für Niedersachsen auf ca. 34 kg NH_3-N/ha, 12 kg PM_{10}/ha, 3 kg $PM_{2.5}$/ha und 6.386 kg $CO_{2äq}$/ha. Im Vergleich zu diesen modellierten Werten sind die Modellergebnisse für Baden-Württemberg bzw. Brandenburg ca. 1,5 bis zweimal so hoch. Vergleicht man diese Emissionen im Referenzscenario mit Werten aus dem nationalen Emissionsinventar, zeigt der Vergleich eine Überschätzung der modellierten Feinstaub- und Treibhausgasemissionen und eine Unterschätzung der NH_3-Verluste. Dies kann durch die folgenden Modellbesonderheiten von EFEM erklärt werden: disaggregierte und prozessorientierte Modellierung der Feinstaubemissionen aus Ackerbau, zusätzliche, an die Realität angenäherte Annahmen für die Berechnung von NH_3-Emissionen und abweichende Aggregation von Informationen der Landwirtschaftszählung. Im Vergleich zur Referenzsituation sind die Emissionsergebnisse der Untersuchungsregionen für das Jahr 2015 für Feinstaub um 4 bis 20%, für NH_3 um 2 bis 10% und für THG insgesamt um 2 bis 20% höher. Niedersachsen weist die höchsten absoluten Steigerungen auf: NH_3-N ist von 81,0 Mio. kg auf 87,1 Mio. kg (ca. +7,6%) gestiegen, Feinstaub von 27,1 Mio. auf 31,1 Mio. kg PM_{10} (+14,7%) und von 6,8 Mio. auf 7,6 Mio. kg $PM_{2.5}$ (+12,0%) und für THG-Emissionen von 15.033 Mio. auf 16.599 Mio. kg $CO_{2äq}$ (+10,4%), wobei in Brandenburg die relative Emissionsänderung für NH_3-N mit +9,4% (von 18,7 Mio. auf 20,4 Mio. kg NH_3-N), für Feinstaub mit +20,7% für PM_{10} und +17,0% für $PM_{2.5}$ (von 10,7 Mio. auf 12,9 Mio. kg PM_{10} und von 2,5 Mio. auf 2,9 Mio. kg $PM_{2.5}$) und für THG mit +19,9% (von 4.687 Mio. auf 5.620 Mio. kg $CO_{2äq}$) am höchsten ist. Allerdings zeigt Baden-Württemberg nur geringe Änderungsraten sowohl für PM_{10} in Höhe von 0,5 Mio. kg PM_{10} und für $PM_{2.5}$ im Umfang von 0,02 Mio. kg $PM_{2.5}$ (+4,8% bzw. +0,9%) als auch Ammoniak in Höhe von 0,6 Mio. kg NH_3-N (+2,0%) und für THG in Höhe von 20,9 Mio. kg $CO_{2äq}$ (+0,3%). Die Werte veranschaulichen, dass die Emissionssituation in

Brandenburg durch die Anpassung agrarpolitischer Rahmenbedingungen am stärksten negativ beeinflusst wird.

Die Wirkung verschiedener Maßnahmen zur Reduktion von NH_3- und Feinstaubbelastungen wird durch den Ergebnisvergleich verschiedener Szenarien mit dem Szenario ‚BAU' dargestellt. Die einzelnen Szenarien untersuchen dabei Anpassungen einzelner Emissionsquellen innerhalb emissionsrelevanter Produktionsverfahren, wie bspw. der Ausschluss von Harnstoff bei der Mineraldüngerapplikation, der Umstieg von Flüssig- auf Festmist basierenden Tierhaltungssystemen, die Einführung von rohproteinreduzierten Futterrationen in der Schweine- und Geflügelproduktion, umweltfreundliche Lagerungs- und Ausbringungssysteme von Flüssigmist, reduzierte Bodenbearbeitung sowie die Installation von Abluftreinigungsanlagen in Schweineställen. Neben der Berechnung von Szenarien für die Einführung von rohproteinreduzierten Fütterung und Aufbau von Abluftreinigungsanlagen wurden auch Simulationen durchgeführt, um die Anpassungen von Modellergebnissen durch die Änderungen von exogenen Parametern abzuleiten.

Obwohl der Ausschluss von Harnstoff aus Düngeverfahren sowohl aus der Perspektive der Landwirte als auch der Politiker relativ einfach umzusetzen wäre, ist das eine teure emissionsmindernde Maßnahme in Bezug auf NH_3-Emissionen - vor allem für Betriebe mit einer relativ hohen Viehdichte. So sinkt der durch die Modellierung ermittelte Deckungsbeitrag für Niedersachsen und Brandenburg von 476 Mio. EUR bzw. 576 Mio. EUR um entsprechend 1,6 bzw. 1,8% für Verbundbetriebe und von 1.722 Mio. EUR bzw. 182 Mio. EUR um etwa jeweils 0,3% für Futterbaubetriebe. Diese Vermeidungsoption hat einen positiven Nebeneffekt, da weiterhin auch NO_2- und THG-Emissionen gemindert werden. Darüber hinaus - im Vergleich zu allen Szenarien der vorliegenden Arbeit - ergibt diese Szenariorechnung eine maximale Senkung von NH_3-Belastungen. Unter allen in dieser Studie untersuchten Emissionsminderungsmaßnahmen führt der Ausschluss von Harnstoff aus Düngeverfahren, aufgrund von mangelndem Ersatz von Mineraldünger durch organischen Dünger, zu einer maximalen Reduktion des durch die Düngung freigesetzten NH_3 um bis zu 89% in Ackerbaubetrieben (5,6 Mio. kg NH_3-N in Niedersachsen, 2,8 Mio. kg NH_3-N in Baden-Württemberg und 3,0 Mio. kg NH_3-N in Brandenburg). Ackerbaubetriebe leisten daher einen Beitrag von 50% zur regionalen Vermeidung. Dementsprechend sind auch die durchschnittlichen Vermeidungskosten für Ackerbaubetriebe am niedrigsten. Die NH_3-Emissionsreduktion ist am effizientesten in Niedersachsen, wo die Flächenausstattungen höher und die Durchschnittsvermeidungskosten um 2,4 EUR/kg NH_3-N niedriger sind als vergleichsweise in Baden-Württemberg und Brandenburg.

Die Kosten für die Umstellung von Flüssig- auf Festmist basierende Haltungssysteme in der Rinderproduktion hängen von den baulichen Anpassungen der Stallgebäude ab. Die höhere Viehbestandsdichte korrespondiert mit dem höchsten Beitrag der gesamten NH_3-Vermeidung und den niedrigsten durchschnittlichen Vermeidungskosten. Obwohl die Einführung dieser Minderungsmaßnahme in Betrieben und Regionen mit einer vergleichsweise hohen Viehdichte zu einer Minderung von NH_3- bzw. THG-Emissionen beiträgt, führt diese jedoch gleichzeitig zu einer bis zu 4% höheren Feinstaubbelastung. Von allen Untersuchungsregionen sind die Durchschnittsvermeidungskosten dieser emissionsmindernden Maßnahme mit ca. 15,3 EUR/kg NH_3-N in Niedersachsen am niedrigsten, das mit durchschnittlich 1,16 GVE (Großvieheinheiten) je ha eine vergleichsweise hohe Viehdichte erreicht.

Neben Anpassungsmaßnahmen für Stallgebäude gibt es in Tierhaltungssystemen weitere Möglichkeiten NH_3-Verluste zu reduzieren, wie bspw. über eine schrittweise Verringerung des Rohprotein-Gehalts in der Tierfütterung. In der Schweinproduktion können positive ökonomische Auswirkungen dieser Minderungsmaßnahme zumindest teilweise durch die Mengenreduzierung der teuren Futtermittelinhaltstoffe mit hohem Anteil an Rohprotein erklärt werden. Die intensiven Tierhaltungsbetriebe mit dem Schwerpunkt Schweineproduktion zeigen die höchste NH_3-Emissionsverminderungseffekte in Höhe von 0,9 Mio. kg NH_3-N (-6,7%) für Niedersachsen, 0,3 Mio. kg NH_3-N (-6,6%) für Baden-Württemberg und 12,3 Mio. kg NH_3-N (-7,8%) für Brandenburg. Die resultierende NH_3-Emissionsminderung fällt jedoch für alle untersuchten Bundesländer gering aus. Maximal werden Minderungen von 1,2 Mio. kg NH_3-N (-1,5%) in der Masthähnchenproduktion in Niedersachsen, etwa 0,2 Mio. kg NH_3-N (-0,8%) in der Zuchtsauenproduktion in Brandenburg bzw. 0,3 Mio. kg NH_3-N (-2,4%) in Baden-Württemberg erreicht. Diese vernachlässigbaren Reduktionsraten, sowohl für NH_3- als auch für THG-Emissionen, werden Landwirte kaum motivieren, rohproteinreduzierte Fütterungssysteme zu implementieren.

Heute ist der Einsatz von umweltfreundlichen Techniken für die Lagerung und Ausbringung von Flüssigmist für die Mehrheit der deutschen Landwirte selbstverständlich. In der vorliegenden Arbeit werden verschiedene Techniken analysiert, die zu einer Reduzierung von NH_3-Emissionen führen, welche für kostengünstige relativ niedrig und für teurere Lösungsoptionen relativ hoch ausfällt. Aufgrund der hohen Viehdichte zeigen intensive Tierhaltungsbetriebe mit dem Schwerpunkt Schweineproduktion als auch Futterbaubetriebe die höchste Emissionsvermeidung. Im Vergleich zu anderen Techniken folgt die Injektion von Flüssigmist direkt in den Boden und die Abdeckung von Güllelagern mit Granulat mit einer vergleichsweise höheren NH_3-Minderung. Eine geringere Reduzierung von NH_3-Emissionen bei höheren

Vermeidungskosten pro Jahr wurde für die Abdeckung von Flüssigmistlagern bei der Verwendung von Granulat als Deckmaterial ermittelt.

Die landwirtschaftlich genutzte Fläche unter konservierender oder reduzierter Bodenbearbeitung nimmt sowohl in Deutschland als auch in der EU insgesamt zu. Diese Verfahren führen zu geringeren Feinstaubbelastungen im Ackerbau und zu einer Steigerung des Deckungsbeitrags aufgrund eines - im Vergleich zur konventionellen Bodenbearbeitung - geringeren Dieselverbrauchs. In Baden-Württemberg und Niedersachsen ist der Beitrag der Ackerbaubetriebe zur regionalen Minderung der Feinstaubbelastung mit 55% bzw. 24% am höchsten (Baden-Württemberg: -2,2 Mio. kg $PM_{2.5}$ und -0,3 Mio. kg PM_{10}; Niedersachsen: -1,7 Mio. kg PM_{10} und -0,2 Mio. kg $PM_{2.5}$). Die Treibhausgasemissionen insgesamt verringern sich vor allem durch CO_2-Bindung um bis zu 80%, d.h., um 15,2 Mrd. kg $CO_{2äq}$ für Niedersachsen, 6,4 Mrd. kg $CO_{2äq}$ für Baden-Württemberg und 5,4 Mrd. kg $CO_{2äq}$ für Brandenburg.

Die Anbringung von Filter- oder Abluftsystemen in Stallanlagen ist aufwendig, stellt jedoch eine effiziente Maßnahme zur Reduzierung von NH_3- und Feinstaubbelastungen dar. Innerhalb der Multi-Schadstofffilter erzielt die Installation von einstufigen chemischen Wäschern eine relativ kostengünstige Bekämpfung von Feinstaub- und NH_3-Belastungen. Eine Sensitivitätsanalyse zeigt, dass je höher die NH_3-Emissionsinstensität ist, desto geringer sind die NH_3-Verluste und Durchschnittsvermeidungskosten. Bei der Sensitivitätsanalyse wurden drei verschiedene NH_3-Emissionsfaktorstufen berücksichtigt, ein minimaler, ein durchschnittlicher sowie ein maximaler Wert. Die Modellrechnung mit dem maximalen NH_3-Emissionsfaktor resultiert im Vergleich zur IST-Situation, die mit dem durchschnittlichen NH_3-Emissionsfaktor abgebildet wurde, bis zu 24% geringere NH_3-Belastungen. Die Durchschnittsvermeidungskosten reduzieren sich dabei um 30%. Allerdings verursacht der Mehraufwand für den Bau von separaten Speichern für Filterabwasser wiederum einen Anstieg der Vermeidungskosten um 30% im Vergleich zur IST-Situation, bei der unterstellt wurde, dass Filterabwasser mit Flüssigmist zusammen gelagert wird. Auf der betrieblichen Ebene ist dadurch die Senkung der Feinstaubbelastung für Tierhaltungsbetriebe mit dem Schwerpunkt Schweineproduktion maximal, hauptsächlich aufgrund der höheren Anzahl von Zuchtsauen, die relativ höhere Feinstaubemissionen verursachen.

Der Netto-Nutzen, als Differenz von eingesparten Kosten für menschliche Gesundheitsschäden und Umweltschäden und den landwirtschaftlichen Vermeidungskosten, gibt einen Einblick auf die gesamtwirtschaftliche Wirkung von Minderungsmaßnahmen. Die in dieser Studie analysierten Emissionsvermeidungsoptionen, die einen maximalen Netto-Nutzen und eine maximale Emissionsminderung gewährleisten, wurden miteinander kombiniert und als Vermeidungsstrategie sowohl auf betrieblicher als auch politischer Ebene empfohlen.

Mit der Ratifizierung des Protokolls von Göteborg hat Deutschland sich verpflichtet, die Emissionen innerhalb eines bestimmten Zeitraumes auf die national festgelegten Emissionsobergrenzen zu reduzieren. Die Wirksamkeit jeder Emissionsvermeidungsmaßnahmen wird deutlich, indem die Szenario-Ergebnisse mit den nationalen Emissionsobergrenzen für die Jahre zwischen 2020 und 2029, die von der Europäischen Kommission vorgeschlagen wurden, vergleicht. Die Effizienz von den Einzelszenarien variiert aufgrund der individuellen regionalen Bedingungen.

Das zunehmende Interesse für Umweltprobleme auf regionaler und globaler Ebene erfordert für die Statusbestimmung des Belastungsgrades und der Emissionsvermeidung mehr Beiträge von Wissenschaftlern aus der ganzen Welt. Die vorliegende Studie und deren Modellierungsergebnisse zeigen die Relevanz für weitere Untersuchungen von Feinstaub-und NH_3-Emissionen aus und in der Landwirtschaft und von Möglichkeiten, diese zu verringern.

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APPENDIXES

Appendix I Scenarios' results for NH_3, PM, and GHG emissions in Lower Saxony

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	**€/ha**	**kg/ha**									**kg CO_2e/ha**				**€/kg NH_3**	**€/kg PM_{10}**	**€/kg $PM_{2.5}$**
Reference	**AF**	1,000	--	6.7	6.7	10.2	1.9	--	--	10.6	2.3	2,551	900	--	3,501	--	--	--
	FGF	1,710	42.2	1.1	43.3	2.9	0.6	0.5	0.3	3.7	1.1	1,882	640	4,398	7,092	--	--	--
	ILF_pigs	3,686	67.2	3.8	70.9	9.7	1.9	4.3	0.7	20.1	4.1	4,228	5,287	1,364	10,918	--	--	--
	ILF_poultry	2,273	48.6	4.2	52.7	10.3	2.0	7.1	1.2	31.8	8.2	3,128	5,666	1,060	8,908	--	--	--
	MF	1,289	18.1	5.2	23.3	8.3	1.6	3.7	0.6	15.9	3.9	2,699	4,629	1,180	5,329	--	--	--
	LS	1,680	30.0	3.8	33.8	7.1	1.3	1.9	0.4	12.0	2.9	2,513	2,249	2,114	6,386	--	--	--
		Changes against the reference, in %																
I[41]	**AF**	-0.7	--	-88.0	-88.0	0.6	0.7	--	--	0.5	0.3	-4.9	-1.6	--	-4.0	0.9	--	--
	FGF	-0.2	-1.0	-82.6	-3.9	-0.1	-0.1	--	--	-0.2	-0.4	-1.2	-0.5	0.1	-0.3	2.6	--	--
	ILF_pigs	-0.8	-0.1	-72.5	-4.9	0.0	0.0	--	--	0.0	-0.1	-1.4	-0.2	0.0	-0.6	8.5	--	--
	ILF_poultry	-0.7	0.0	-83.8	-8.7	0.0	0.0	--	--	-0.1	-0.2	-5.2	-0.7	0.0	-2.2	3.3	--	--
	MF	-1.6	0.0	-82.3	-22.7	0.0	0.0	--	--	-0.2	-0.2	-2.1	-0.9	-1.9	-1.7	3.5	--	--
	LS	-0.6	-0.5	-84.6	-14.8	0.2	0.3	--	--	0.1	-0.1	-2.9	-0.7	-0.1	-1.4	2.4	--	--
II[42]	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-5.8	-15.9	-3.7	-15.6	1.0	1.9	10.2	9.9	26.6	16.6	-14.0	-4.7	-14.6	-15.6	14.8	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	MF	-1.7	5.6	4.0	-3.4	0.0	0.0	0.4	1.6	0.1	0.3	0.4	0.4	-9.7	-3.4	28.2	--	--
	LS	-2.5	-9.1	0.4	-8.1	0.2	0.3	1.1	3.2	3.3	2.5	-4.0	-0.8	-12.6	-6.0	15.3	--	--
III[43] **(Sows)**	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	3.0	-7.4	5.7	-6.7	--	--	--	--	-2.4	-2.6	-2.0	-1.3	-1.4	-2.8	-24.4	--	--
	ILF_poultry	-0.1	-6.5	1.4	-5.8	--	--	--	--	--	--	-1.6	0.5	0.0	-0.5	1.1	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	0.5	-5.6	0.8	-1.8	--	--	--	--	-0.3	-0.2	-0.4	-0.1	-0.1	-0.4	-11.4	--	--
III (Fattened pigs)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	1.2	-0.2	--	-0.2	--	--	--	--	--	--	0.0	0.0	-8.7	-1.2	-431	--	--
	ILF_poultry	1.8	-0.3	0.2	-0.2	--	--	--	--	--	--	0.0	0.0	-10.2	-1.7	-348	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	0.5	-0.2	0.2	-0.1	--	--	--	--	--	--	0.0	0.1	-0.9	-0.3	-359	--	--

41 I – Scenario I: Abdication of urea in mineral fertilizers
42 II – Scenario II: Change of housing system
43 III – Scenarios III: Protein adjusted feeding of livestock, i.e., for pigs (sows and fattened pigs) and poultry (laying hens and broilers)

Appendix I Scenarios' results for NH_3, PM, and GHG emissions in Lower Saxony (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	Changes against the reference, in %														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
III[44] (Laying hens)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	-5.5	-3.3	-2.1	-3.2	--	--	--	--	-30.1	-45.0	-0.6	5.5	0.0	3.7	79.8	--	--
	MF	-1.6	-0.5	0.0	-0.4	--	--	--	--	-8.5	-13.3	-0.1	2.0	2.1	1.4	223	--	--
	LS	-1.1	-0.7	-0.3	-1.2	--	--	--	--	-11.2	-17.6	-0.1	1.8	0.2	0.7	84.0	--	--
III (Broilers)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	-1.5	-0.6	0.3	-0.5	--	--	--	--	-0.8	-2.0	-0.1	1.1	--	0.8	141	--	--
	MF	-9.6	-4.7	-0.4	-3.9	-0.2	-0.2	--	--	-5.5	-13.4	-1.1	9.4	3.0	3.9	133	--	--
	LS	-1.3	-1.2	-0.1	-0.9	0.0	0.0	--	--	-1.3	-3.2	-0.2	1.6	0.2	0.5	55.4	--	--
IV[45] (Granulate)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-0.2	-8.7	-5.2	-8.6	--	--	0.0	0.0	0.0	-0.1	0.2	-0.5	-0.1	0.0	1.1	--	--
	ILF_pigs	-0.8	-14.3	-5.1	-13.8	0.0	0.1	0.0	0.0	0.1	0.6	3.6	1.3	0.0	1.7	3.1	--	--
	ILF_poultry	-0.4	-8.9	-10.5	-9.1	--	--	0.0	0.0	0.0	-0.1	-2.2	-0.4	0.0	-0.9	2.1	--	--
	MF	-0.2	-2.7	-0.3	-2.2	--	--	--	--	--	--	0.0	-0.1	1.9	-0.5	5.2	--	--
	LS	-0.3	-9.2	-2.6	-8.5	--	--	--	--	--	--	0.1	0.0	-0.2	0.0	2.0	--	--
IV (Floating film)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-0.9	-10.9	-3.4	-10.7	0.0	0.0	--	--	0.0	-0.2	0.8	-0.5	0.0	0.2	3.3	--	--
	ILF_pigs	-1.2	-14.2	-5.1	-13.7	0.1	0.1	--	--	0.1	0.6	3.5	1.3	0.0	1.8	4.6	--	--
	ILF_poultry	-0.9	-8.9	-10.5	-9.1	0.0	0.0	--	--	0.0	-0.1	-2.2	-0.4	0.0	-0.9	4.3	--	--
	MF	-0.9	-2.7	-0.3	-2.2	--	--	--	--	0.0	0.0	0.0	-0.1	0.0	0.0	23.6	--	--
	LS	-0.8	-10.4	-2.2	-9.5	--	--	--	--	0.0	0.0	0.4	0.1	0.0	0.2	4.2	--	--
IV (Hexa-cover)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-0.4	-6.4	-3.0	-6.3	0.0	0.0	--	--	0.0	-0.1	1.0	-0.6	0.0	0.2	2.6	--	--
	ILF_pigs	-1.0	-14.2	-5.1	-13.7	0.0	0.0	--	--	0.1	0.6	3.6	1.3	0.1	1.8	3.8	--	--
	ILF_poultry	-0.6	-8.9	-10.5	-9.1	0.0	0.0	--	--	0.0	-0.1	-2.2	-0.4	0.0	-0.9	3.1	--	--
	MF	-0.4	-2.7	-0.3	-2.2	--	--	--	--	--	--	0.0	-0.1	0.1	0.0	11.1	--	--
	LS	-0.5	-8.0	-2.3	-7.3	0.0	0.0	--	--	0.0	0.0	0.3	0.0	0.0	0.1	3.3	--	--

[44] III – Scenarios III: Protein adjusted feeding of livestock, i.e., for pigs (sows and fattened pigs) and poultry (laying hens and broilers)

[45] IV – Scenario IV: Introduction of the manure storage cover (Scenario IV), i.e., granulate, floating film, Hexa-cover, tent roof, concrete cover, and vehicle-access concrete cover

Appendix I Scenarios' results for NH_3, PM, and GHG emissions in Lower Saxony (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	Changes against the reference, in %														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
IV[46] (Tent roof)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-0.9	-10.1	-4.1	-10.0	--	--	--	--	--	--	0.7	-0.7	0.0	0.1	3.5	--	--
	ILF_pigs	-1.3	-15.6	-5.6	-15.0	0.0	0.1	--	--	0.2	0.7	3.6	1.4	0.0	1.8	4.5	--	--
	ILF_poultry	-0.9	-9.8	-11.5	-9.9	0.0	0.0	--	--	0.0	-0.1	-2.6	-0.4	0.0	-1.0	4.1	--	--
	MF	-0.9	-3.0	-0.3	-2.4	--	--	--	--	--	--	0.0	0.0	-0.5	-0.1	21.6	--	--
	LS	-0.8	-10.4	-2.6	-9.5	0.0	0.0	--	--	0.2	0.2	0.2	0.0	0.1	0.1	4.3	--	--
IV (Concrete cover)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-1.0	-6.5	-5.8	-6.5	0.0	0.0	--	--	0.0	-0.2	0.3	-0.1	-0.1	0.0	6.2	--	--
	ILF_pigs	-1.1	-15.6	-5.6	-15.1	0.0	0.0	--	--	0.2	0.7	3.9	1.4	0.1	2.0	3.7	--	--
	ILF_poultry	-0.6	-9.8	-11.5	-9.9	0.0	0.0	--	--	0.0	-0.1	-2.6	-0.4	0.0	-1.0	2.6	--	--
	MF	-0.6	-3.0	-0.3	-2.4	--	--	--	--	--	--	0.0	0.0	-0.5	-0.1	13.6	--	--
	LS	-0.7	-8.4	-2.7	-7.8	0.0	0.0	--	--	0.0	0.0	0.2	0.1	0.1	0.1	4.8	--	--
IV (V.-a. concrete cover)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-1.1	-13.3	-4.1	-13.1	0.0	0.0	--	--	0.0	-0.1	0.7	-0.7	0.0	0.1	3.3	--	--
	ILF_pigs	-1.1	-15.7	-5.6	-15.1	0.0	0.0	--	--	2.0	0.7	3.6	1.4	0.0	1.8	3.7	--	--
	ILF_poultry	-0.7	-9.8	-11.5	-9.9	0.0	0.0	--	--	0.0	-0.1	-2.6	-0.4	0.0	-1.0	3.0	--	--
	MF	-0.6	-3.0	-0.3	-2.4	--	--	--	--	--	--	0.0	0.0	-2.5	-0.5	14.3	--	--
	LS	-0.8	-12.1	-2.6	-11.1	0.0	0.0	--	--	0.0	0.0	0.2	0.0	-0.2	0.0	3.6	--	--
V[47] (Trailing shoe)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-3.0	-22.0	-14.4	-21.8	--	--	--	--	0.0	0.0	-4.0	-2.1	0.0	-1.2	5.6	--	--
	ILF_pigs	-1.7	-7.0	-1.2	-6.7	--	--	--	--	0.0	0.0	-0.3	-0.1	0.0	-0.2	13.5	--	--
	ILF_poultry	-1.2	-5.0	-2.1	-4.7	--	--	--	--	0.0	0.0	-1.1	-0.2	0.0	-0.5	11.2	--	--
	MF	-0.8	-7.4	-0.9	-5.9	--	--	--	--	0.0	0.0	-0.8	-0.4	1.6	-0.9	7.9	--	--
	LS	-1.8	-14.8	-2.4	-13.4	--	--	--	--	0.0	0.0	-1.6	-0.5	-0.1	-0.8	6.8	--	--
V (Slurry extirpator)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-3.5	-24.9	-15.0	-24.7	--	--	--	--	0.0	0.0	-4.1	-2.2	0.0	-1.2	5.7	--	--
	ILF_pigs	-1.8	-7.6	-1.2	-7.2	--	--	--	--	0.0	0.0	-0.5	-0.1	0.1	-0.2	13.3	--	--
	ILF_poultry	-1.3	-5.1	-2.1	-4.8	--	--	--	--	0.0	0.0	-1.1	-0.2	0.0	-0.5	11.5	--	--
	MF	-0.9	-8.1	-0.9	-6.5	--	--	--	--	0.0	0.0	-0.8	-0.5	-1.3	-0.8	7.7	--	--
	LS	-2.0	-16.5	-2.4	-14.9	--	--	--	--	0.0	0.0	-1.7	-0.6	-0.1	-0.8	6.7	--	--

[46] IV – Scenario IV: Introduction of the manure storage cover (Scenario IV), i.e., granulate, floating film, Hexa-cover, tent roof, concrete cover, and vehicle-access concrete cover

[47] V – Scenario V: Manure land application, i.e., through the implementation of slurry spreading techniques as trailing shoe and slurry extirpator

Appendix I Scenarios' results for NH_3, PM and GHG emissions in Lower Saxony (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	Changes against the reference, in %														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
VIa[48]	AF	11.5	--	2.3	2.3	-23.9	-18.6	--	--	-22.4	-13.3	2.9	-36.2*	--	-30.0	--	-48.4	-371
	FGF	2.6	-0.3	14.3	0.0	-42.4	-32.7	--	--	-33.2	-14.8	5.0	-41.4*	0.3	-9.2	--	-35.7	-263
	ILF_pigs	3.7	0.7	-3.8	0.4	-52.9	-39.4	--	--	-22.7	-14.3	0.2	-16.1*	3.0	-20.1	--	-30.1	-233
	ILF_poultry	7.7	0.0	5.2	0.4	-55.0	-40.7	--	--	-17.1	-8.6	4.1	-31.8*	0.0	-39.1	--	-32.1	-248
	MF	9.3	0.1	2.7	0.6	-50.4	-37.9	--	--	-25.9	-13.6	3.1	-48.1*	-0.6	-36.1	--	-29.1	-225
	LS	5.8	-0.1	3.6	0.3	-39.9	-30.3	--	--	-22.8	-12.1	3.4	-32.6*	0.4	-21.1	--	-35.6	-273
VIb[49]	AF	13.3	--	2.3	2.3	-23.9	-18.6	--	--	-22.4	-13.3	2.9	-61.5*	--	-30.0	--	-56.1	-430
	FGF	3.1	-4.4	14.2	-3.9	-42.6	-32.8	--	--	-33.2	-14.7	4.8	-19.7*	0.4	-9.2	--	-42.8	-319
	ILF_pigs	4.7	0.1	-3.8	-0.1	-53.2	-39.7	--	--	-21.3	-13.2	-0.5	-7.2*	0.0	-21.2	--	-40.7	-319
	ILF_poultry	9.4	0.0	5.2	0.4	-55.0	-40.7	--	--	-17.1	-8.6	4.1	-48.0*	0.0	-39.0	--	-39.2	-302
	MF	11.5	0.1	2.7	0.6	-50.4	-37.9	--	--	-25.9	-13.5	3.1	-58.2*	-2.5	-36.4	--	-36.0	-278
	LS	7.0	-2.4	3.6	-1.7	-40.0	-30.3	--	--	-22.6	-12.0	3.3	-37.0*	0.1	-21.2	--	-43.3	-332
VII[50] (Biofilter)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-2.3	-12.2	-28.9	-14.6	--	--	-92.9	-68.7	-22.5	-16.8	-5.8	-8.2	3.2	-8.6	--	18.9	119
	ILF_poultry	-2.1	-10.6	-10.2	-10.6	--	--	-39.1	-28.5	-7.1	-3.3	14.5	3.0	0.0	1.0	--	22.3	188
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	-0.7	-7.4	-7.8	-7.4	--	--	-34.7	-20.3	-5.3	-3.0	0.9	-1.1	0.0	-1.3	--	17.8	128
VII (Trickle bed reactor)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-12.1	-49.6	-10.3	-44.0	--	--	-93.0	-69.0	-20.3	-13.0	-4.3	-2.3	2.0	-2.8	11.9	110	814
	ILF_poultry	-10.1	-48.3	-7.0	-45.1	--	--	-39.1	-28.5	-8.9	-4.4	-5.0	-0.8	0.0	-2.6	10.1	87.4	676
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	-3.9	-20.4	-2.9	-18.2	--	--	-34.7	-20.4	-5.6	-3.0	-1.1	-0.7	-0.1	-0.8	10.6	100	756
VII (2-stage chemical scrubber)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-12.7	-50.2	-10.3	-44.5	--	--	-93.0	-69.0	-20.3	-13.0	-4.8	-2.3	2.0	-3.0	12.4	116	855
	ILF_poultry	-11.3	-47.6	-7.0	-44.5	--	--	-39.1	-28.5	-8.9	-4.4	-5.0	-0.8	0.0	-2.6	11.5	97.8	757
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	-4.2	-19.4	-3.1	-17.3	--	--	-34.7	-20.4	-5.6	-3.0	-1.2	-0.8	0.1	-0.8	12.1	108	813

[48] VIa – Scenario VIa: Reduced tillage, without financial aid
[49] VIb – Scenario VIb: Reduced tillage with financial aid
[50] VII – Scenario VII: Exhaust air treatment, i.e., through the application of biofilter, trickle-bed reactor, 2-stage and 1-stage chemical scrubber, 3-stage filter with 2 water stages, and 3-stage filter with 1 water stage
* – soil carbon sequestration is considered

Appendix I Scenarios' results for NH_3, PM, and GHG emissions in Lower Saxony (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	Changes against the reference, in %														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
VII[51] (1-stage chemical scrubber)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-7.2	-50.7	-10.4	-44.9	--	--	-93.0	-69.0	-20.3	-13.0	-4.8	-2.3	2.0	-3.0	6.9	65.0	481
	ILF_poultry	-5.2	-49.0	-7.1	-45.8	--	--	-39.1	-28.5	-8.9	-4.4	-5.1	-0.9	0.0	-2.7	5.2	45.3	350
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	-2.2	-21.9	-3.0	-19.5	--	--	-34.7	-20.4	-5.6	-3.0	-1.2	-0.7	0.1	-0.7	5.6	56.4	426
VII (3-stage with 2 water stages)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-11.9	-50.7	-10.4	-44.9	--	--	-93.0	-69.0	-20.3	-13.0	-4.8	-2.3	2.0	-3.0	11.5	108	800
	ILF_poultry	-10.8	-34.1	-7.1	-32.0	--	--	-39.1	-28.5	-8.9	-4.4	-3.6	-0.9	0.0	-2.1	15.3	93.8	726
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	-4.0	-16.9	-3.2	-15.2	--	--	-34.7	-20.4	-5.6	-3.0	-1.1	-0.8	-0.1	-0.8	13.1	102	771
VII (3-stage with 1 water stage)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-11.6	-49.2	-10.4	-43.6	--	--	-93.0	-69.0	-20.3	-13.0	-4.8	-2.3	2.0	-3.0	11.5	105	779
	ILF_poultry	-10.6	-49.0	-7.1	-45.8	--	--	-39.1	-28.5	-8.9	-4.4	-5.1	-0.9	0.0	-2.7	10.5	91.8	710
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	LS	-3.9	-21.3	-3.2	-19.0	--	--	-34.7	-20.4	-5.6	-3.0	-1.3	-0.8	-0.1	-0.9	10.2	99.8	751
VIII[52]	AF	7.1	--	-87.3	-87.3	-23.9	-18.6	--	--	-22.7	-14.5	-3.2	-1.4	--	-38.4	-12.1	-29.5	-210
	FGF	-2.4	-24.2	-81.9	-25.8	-41.8	-32.2	3.7	3.6	-33.3	-16.9	-5.4	-5.1	-5.1	-13.7	4.0	33.6	219
	ILF_pigs	-14.8	-64.1	-78.6	-64.9	-54.4	-40.5	-94.2	-74.1	-49.8	-35.7	-27.4	-20.7	-34.8	-52.8	11.8	54.4	370
	ILF_poultry	-0.8	-56.7	-78.0	-58.4	-55.3	-41.0	-39.1	-28.5	-55.0	-56.7	-18.4	2.5	-4.7	-40.9	0.6	1.1	4.1
	MF	2.2	-35.5	-80.5	-45.6	-50.5	-38.1	0.3	1.0	-34.5	-27.1	-6.1	4.0	-9.3	-38.7	-2.6	-5.1	-26.4
	LS	-2.3	-39.1	-83.4	-44.2	-40.1	-30.4	-33.7	-19.4	-40.1	-33.7	-9.4	-4.5	-6.9	-29.6	2.6	8.0	38.5

Notes: AF – arable farm, FGF – forage growing farm, ILF_pigs and ILF_poultry – intensive livestock farms with the emphasis on pigs and poultry production respectively, MF – mixed farms; LS – Lower Saxony.

[51] VII – Scenario VII: Exhaust air treatment, i.e., through the application of biofilter, trickle-bed reactor, 2-stage and 1-stage chemical scrubber, 3-stage filter with 2 water stages, and 3-stage filter with 1 water stage

[52] VIII – Scenario VIII: Combination scenario, i.e., combination of different emissions abatement measures

Appendix II Scenarios' results for NH_3, PM, and GHG emissions in Baden-Württemberg

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	€/ha	kg/ha									kg CO_2e/ha				€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
Reference	AF	779	--	6.4	6.4	10.3	1.9	--	--	10.9	2.4	2,673	1,193	--	3,861	--	--	--
	FGF	1,450	30.8	0.7	31.5	2.3	0.4	0.4	0.2	3.0	0.9	1,403	755	3,443	5,496	--	--	--
	ILF_pigs	3,587	51.7	3.1	54.8	10.5	2.0	3.0	0.5	15.2	3.0	3,235	4,161	746	6,929	--	--	--
	ILF_poultry	1,575	27.1	4.6	31.7	9.1	1.7	6.6	1.1	25.1	6.3	2,651	4,832	1,326	7,450	--	--	--
	MF	1,117	14.6	2.2	16.9	5.3	1.0	0.8	0.3	7.8	2.1	1,556	919	1,755	4,200	--	--	--
	BW	1,323	19.3	3.0	22.3	6.1	1.1	0.7	0.2	7.8	1.9	1,967	1,258	1,797	4,856	--	--	--
		Changes against the reference, in %																
I[53]	AF	-3.1	--	-82.8	-82.8	0.0	0.2	--	--	-0.1	-0.3	-5.8	-1.8	--	-4.5	3.4	--	--
	FGF	-0.2	0.8	-83.1	-1.6	-0.7	-1.2	--	--	-0.6	-0.5	-1.5	-0.2	-0.2	-0.5	5.1	--	--
	ILF_pigs	-0.3	0.0	-83.7	-5.4	0.0	0.1	--	--	3.4	2.5	-4.4	5.2	0.0	0.4	3.5	--	--
	ILF_poultry	-1.1	0.0	-83.3	-15.2	0.0	0.1	--	--	1.0	0.5	-5.6	2.0	0.0	-1.0	3.3	--	--
	MF	-0.8	0.0	-82.5	-13.8	-0.1	-0.2	--	--	-0.2	-0.4	-2.4	-1.2	0.2	-1.0	3.4	--	--
	BW	-0.8	0.5	-82.9	-13.3	-0.1	-0.1	--	--	0.4	0.1	-3.8	0.3	-0.1	-1.5	3.6	--	--
II[54]	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-5.1	-12.9	21.7	-12.1	0.5	1.5	9.1	8.8	24.7	15.4	-11.0	-3.1	-15.0	-12.6	19.3	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	MF	-1.2	2.8	16.9	4.7	1.3	1.4	1.5	2.5	1.0	1.0	6.1	0.6	-8.9	-1.3	-17.6	--	--
	BW	-2.4	-7.2	5.0	-5.5	0.3	0.5	2.2	4.4	3.8	3.0	-1.8	-0.6	-12.9	-5.6	22.4	--	--
III[55] (Sows)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	1.9	-7.4	7.2	-6.6	--	--	--	--	0.6	1.2	-2.4	5.2	-1.0	-1.3	-19.2	--	--
	ILF_poultry	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	0.4	-3.4	0.6	-2.3	--	--	--	--	0.1	0.1	-0.3	0.8	0.1	-0.1	-18.8	--	--
III (Fattened pigs)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	0.6	-0.1	3.5	0.1	--	--	--	--	-0.2	-0.1	0.8	--	-8.4	-0.7	783	--	--
	ILF_poultry	2.7	-8.0	2.1	-6.6	--	--	--	--	0.2	0.2	-1.2	0.6	-5.9	-1.3	-22.7	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	0.2	-1.1	0.4	-0.6	--	--	--	--	0.0	0.0	0.0	0.0	-0.4	-0.1	-46.3	--	--

[53] I – Scenario I: Abdication of urea in mineral fertilizers
[54] II – Scenario II: Change of housing system
[55] III – Scenarios III: Protein adjusted feeding of livestock, i.e., for pigs (sows and fattened pigs) and poultry (laying hens and broilers)

Appendix II Scenarios' results for NH_3, PM, and GHG emissions in Baden-Württemberg (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ farm type	**Changes against the reference, in %**														**€/kg NH_3**	**€/kg PM_{10}**	**€/kg $PM_{2.5}$**
III[56] (Laying hens)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	--	-0.2	3.3	0.0	--	--	--	--	0.1	0.1	0.7	0.5	0.4	0.9	-31.2	--	--
	ILF_poultry	-4.8	-1.3	0.1	-1.1	--	--	--	--	-23.9	-18.0	-0.3	4.2	3.5	3.4	243	--	--
	MF	-1.9	-0.7	0.1	-0.6	--	--	--	--	-36.9	-25.0	-0.1	3.6	-0.3	0.9	221	--	--
	BW	-0.5	-0.5	0.3	-0.3	--	--	--	--	-6.2	-9.7	0.1	1.1	0.0	0.4	190	--	--
III (Broilers)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	--	0.2	3.3	--	--	--	--	--	-0.2	-0.1	0.7	0.1	--	0.5	-2.0	--	--
	ILF_poultry	-2.6	-1.7	0.3	-1.4	--	--	--	--	-1.3	-3.2	-0.2	-1.7	3.0	1.8	101	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	-0.1	0.0	0.3	0.0	--	--	--	--	-0.1	-0.3	0.1	0.1	0.0	0.1	382	--	--
V[57] (Granulate)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-0.3	-5.7	-5.3	-5.7	0.0	0.0	--	--	-0.2	-0.6	0.7	1.0	--	0.1	2.5	--	--
	ILF_pigs	-0.1	-13.0	-6.0	-12.6	0.0	0.0	--	--	-0.1	-0.3	2.1	-0.9	--	0.8	0.3	--	--
	ILF_poultry	-0.4	-6.1	-1.4	-5.4	--	--	--	--	--	--	0.3	-0.2	--	0.0	3.4	--	--
	MF	-0.3	-5.3	-1.2	-4.8	--	--	--	--	--	--	-0.1	-0.3	--	-0.1	3.8	--	--
	BW	-0.2	-7.0	-1.2	-6.2	0.0	0.0	--	--	0.0	-0.1	0.4	-0.4	--	0.1	2.0	--	--
IV (Floating film)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-1.1	-6.9	-4.6	-6.8	0.0	0.0	--	--	0.0	-0.1	0.8	-0.6	0.0	0.2	7.3	--	--
	ILF_pigs	-0.6	-12.9	-6.0	-12.5	0.0	0.0	--	--	-0.1	-0.3	2.1	-0.9	0.0	0.8	3.0	--	--
	ILF_poultry	-1.5	-6.2	-1.4	-5.5	--	--	--	--	--	--	0.3	-0.2	3.7	0.7	13.7	--	--
	MF	-1.3	-5.3	-1.2	-4.8	--	--	--	--	--	--	-0.1	-0.3	-0.1	-0.1	19.4	--	--
	BW	-0.9	-7.7	-1.1	-6.8	0.0	0.0	--	--	0.0	-0.1	0.5	-0.3	0.0	0.1	7.7	--	--
IV (Hexa-cover)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-0.5	-3.4	-4.6	-3.7	0.0	0.0	--	--	0.0	-0.1	0.9	-0.6	0.0	0.2	6.3	--	--
	ILF_pigs	-0.2	-13.0	-6.0	-12.6	0.0	0.0	--	--	-0.1	-03	2.1	-0.9	0.0	0.8	1.2	--	--
	ILF_poultry	-0.7	-6.2	-1.4	-5.5	--	--	--	--	--	--	0.3	-0.2	0.0	0.0	6.2	--	--
	MF	-0.6	-5.3	-1.2	-4.8	--	--	--	--	--	--	0.1	-0.3	-0.1	-0.1	9.3	--	--
	BW	-0.4	-5.8	-1.1	-5.1	0.0	0.0	--	--	0.0	-0.1	0.5	-0.3	0.0	0.1	4.8	--	--

[56] III – Scenarios III: Protein adjusted feeding of livestock, i.e., for pigs (sows and fattened pigs) and poultry (laying hens and broilers)

[57] IV – Scenario IV: Introduction of the manure storage cover (Scenario IV), i.e., granulate, floating film, Hexa-cover, tent roof, concrete cover, and vehicle-access concrete cover

Appendix II Scenarios' results for NH_3, PM, and GHG emissions in Baden-Württemberg (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	**Changes against the reference, in %**														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
IV[58] (Tent roof)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-1.1	-6.0	-5.4	-5.9	0.0	0.0	--	--	-0.1	-0.2	0.8	-0.7	0.0	0.2	8.5	--	--
	ILF_pigs	-0.6	-14.3	-6.6	-13.9	0.0	0.0	--	--	-0.1	-0.3	2.0	-1.0	0.0	0.7	2.8	--	--
	ILF_poultry	-1.5	-7.0	-1.5	-6.2	0.0	0.0	--	--	0.0	-0.1	0.2	-0.2	0.0	0.0	12.2	--	--
	MF	-1.3	-6.2	-1.4	-5.6	0.0	0.0	--	--	0.0	-0.1	-0.1	-0.3	-0.2	0.0	16.5	--	--
	BW	-0.9	-7.6	-1.2	-6.7	0.0	0.0	--	--	0.0	-0.1	0.4	-0.4	0.0	0.1	7.8	--	--
IV (Concrete cover)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-1.2	-6.0	-5.4	-5.9	0.0	0.0	--	--	-0.1	-0.2	0.8	-0.7	0.0	0.2	9.6	--	--
	ILF_pigs	-0.3	-14.3	-6.7	-13.9	0.0	0.0	--	--	-0.1	-0.3	2.2	-0.9	0.0	0.8	1.2	--	--
	ILF_poultry	-0.9	-7.0	-1.5	-6.2	0.0	0.0	--	--	0.0	-0.1	0.2	-0.2	1.3	0.2	7.3	--	--
	MF	-0.8	-6.2	-1.4	-5.6	0.0	0.0	--	--	0.0	-0.1	-0.1	-0.3	0.0	-0.1	9.8	--	--
	BW	-0.7	-7.6	-1.3	-6.7	0.0	0.0	--	--	0.0	-0.1	0.5	-0.4	0.0	0.1	6.6	--	--
IV (V.-a. concrete cover)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-1.3	-4.1	-5.4	-4.1	0.0	0.0	--	--	-0.1	-0.2	0.9	-0.7	0.0	0.2	14.6	--	--
	ILF_pigs	-0.3	-14.2	-6.6	-13.8	0.0	0.0	--	--	-0.1	-0.3	2.0	-1.0	0.0	0.7	1.4	--	--
	ILF_poultry	-1.0	-6.9	-1.4	-6.1	0.0	0.0	--	--	-0.1	-0.1	0.3	-0.3	0.0	0.0	7.8	--	--
	MF	-0.9	-6.2	-1.4	-5.6	0.0	0.0	--	--	0.0	-0.1	0.1	-0.3	-0.1	-0.1	10.7	--	--
	BW	-0.8	-6.5	-1.2	-6.7	0.0	0.0	--	--	0.0	-0.1	0.4	-0.4	0.0	0.1	8.3	--	--
V[59] (Trailing shoe)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-3.1	-17.2	-21.4	-17.3	--	--	--	--	0.0	0.0	-4.5	-2.9	0.1	-1.3	8.3	--	--
	ILF_pigs	-1.5	-7.9	-3.6	-7.6	--	--	--	--	0.0	0.0	-1.5	-0.4	0.0	-0.8	12.7	--	--
	ILF_poultry	-2.6	-4.4	-0.8	-4.0	--	--	--	--	0.0	0.0	-0.6	-0.2	1.3	-0.1	33.9	--	--
	MF	-1.6	-17.2	-3.9	-15.4.	--	--	--	--	0.0	0.0	-2.5	-1.0	-0.7	-1.3	7.0	--	--
	BW	-1.9	-15.0	-2.8	-13.3	--	--	--	--	0.0	0.0	-1.9	-0.8	-0.1	-0.9	8.7	--	--
V (Slurry extirpator)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-3.4	-21.0	-21.6	-21.0	--	--	--	--	0.0	0.0	-4.6	-2.9	0.1	-1.3	7.6	--	--
	ILF_pigs	-1.6	-7.9	-3.6	-7.6	--	--	--	--	0.0	0.0	-1.5	-0.4	0.0	-0.8	13.7	--	--
	ILF_poultry	-2.8	-4.9	-0.5	-4.3	--	--	--	--	0.0	0.0	-0.5	-0.6	0.0	-0.5	32.3	--	--
	MF	-1.8	-18.5	-3.9	-16.5	--	--	--	--	0.0	0.0	-2.6	-0.9	-0.3	-1.2	7.4	--	--
	BW	-2.1	-17.5	-2.9	-15.5	--	--	--	--	0.0	0.0	-1.9	-0.8	0.0	-0.9	8.4	--	--

[58] IV – Scenario IV: Introduction of the manure storage cover (Scenario IV), i.e., granulate, floating film, Hexa-cover, tent roof, concrete cover, and vehicle-access concrete cover
[59] V – Scenario V:Manure land application, i.e., through the implementation of slurry spreading techniques as trailing shoe and slurry extirpator

Appendix II Scenarios' results for NH_3, PM, and GHG emissions in Baden-Württemberg (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	Changes against the reference, in %														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
VIa[60]	AF	10.3	--	-8.6	-8.6	-52.4	-40.4	--	--	-49.7	-31.3	-6.5	-73.3*	--	-72.5	--	-14.8	-104
	FGF	1.5	5.1	-16.1	4.6	-38.2	-32.3	--	--	-30.2	-16.0	0.8	-49.7*	-0.1	-11.8	--	-24.4	-151
	ILF_pigs	1.4	1.3	-7.0	0.9	-46.0	-35.9	--	--	-26.9	-18.5	-1.6	-35.8*	0.0	-38.4	--	-11.9	-86.4
	ILF_poultry	4.5	0.3	-0.7	0.1	-54.5	-42.9	--	--	-17.6	-10.1	1.0	-37.0*	4.0	-40.7	--	-16.0	-113
	MF	3.2	-1.0	-6.1	-1.7	-50.7	-39.2	--	--	-34.3	-17.9	-0.8	-80.0*	0.3	-39.2	--	-13.3	-93.8
	BW	3.4	3.1	-8.4	1.6	-49.4	-38.6	--	--	-37.6	-22.0	-2.4	-61.7*	0.1	-34.8	--	-15.4	-107
VIb[61]	AF	17.6	--	-8.9	-8.9	-56.2	-43.0	--	--	-53.2	-33.4	-6.8	-79.0*	--	-77.7	--	-23.7	-168
	FGF	2.2	2.7	-10.3	2.4	-44.1	-36.3	--	--	-34.8	-17.5	1.5	-54.1*	-0.1	-12.8	--	-30.5	-197
	ILF_pigs	3.0	0.5	-26.8	-1.0	-53.9	-40.7	--	--	-25.2	-16.1	-6.2	-32.5*	0.0	-42.6	--	-27.7	-217
	ILF_poultry	7.6	0.7	-0.7	0.5	-56.9	-44.5	--	--	-18.5	-10.5	0.9	-38.6*	3.9	-42.4	--	-25.9	-183
	MF	5.7	-0.5	-6.0	-1.2	-52.6	-40.3	--	--	-35.6	-18.5	-0.8	-84.9*	0.4	-41.1	--	-23.1	-163
	BW	5.9	1.7	-9.4	0.2	-53.5	-41.2	--	--	-39.9	-22.9	-2.8	-65.3*	0.1	-37.2	--	-24.9	-175
VII[62] (Biofilter)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-6.4	-15.9	41.6	-13.8	--	--	-94.0	-72.0	-18.9	-10.6	-2.7	4.5	0.0	1.5	--	89.3	806
	ILF_poultry	-4.5	-21.3	19.4	-17.0	--	--	-48.0	-35.2	-12.5	-5.7	-2.4	3.1	0.3	2.2	--	25.8	228
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	-1.4	-5.5	3.0	-4.4	--	--	-39.6	-15.9	-3.4	-1.5	-0.4	0.9	0.0	0.2	--	71.3	657
VII (Trickle bed reactor)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-12.6	-50.2	-2.3	-48.4	--	--	-94.0	-72.0	-19.2	-12.2	-4.9	-0.3	-0.2	-2.8	15.4	173	1,374
	ILF_poultry	-11.0	-29.3	0.1	-26.2	--	--	-48.0	-35.2	-12.9	-6.5	-1.9	0.0	4.6	0.4	22.0	61.3	490
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	-2.8	-12.9	-0.1	-11.3	--	--	-39.6	-15.9	-3.5	-1.8	-0.7	0.0	0.2	-0.2	14.6	140	1,113
VII (2-stage chemical scrubber)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-13.6	-49.6	-2.3	-47.8	--	--	-94.0	-72.0	-19.3	-12.2	-4.8	-0.3	-0.2	-2.8	16.9	187	1,489
	ILF_poultry	-12.1	-29.2	0.1	-26.1	--	--	-48.0	-35.2	-12.9	-6.5	-1.9	0.0	5.2	0.5	24.2	67.2	537
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	-3.1	-11.3	-0.1	-9.9	--	--	-39.6	-15.9	-3.5	-1.8	-0.6	0.0	0.2	-0.2	18.1	153	1,241

[60] VIa – Scenario VIa: Reduced tillage, without financial aid
[61] VIb – Scenario VIb: Reduced tillage with financial aid
[62] VII – Scenario VII: Exhaust air treatment, i.e., through the application of biofilter, trickle-bed reactor, 2-stage and 1-stage chemical scrubber, 3-stage filter with 2 water stages, and 3-stage filter with 1 water stage
* – soil carbon sequestration is considered

Appendix II Scenarios' results for NH_3, PM, and GHG emissions in Baden-Württemberg (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	Changes against the reference, in %														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
VII[63] (1-stage chemical scrubber)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-7.8	-50.1	-2.4	-48.3	--	--	-94.0	-72.0	-19.2	-12.2	-4.6	-0.3	-0.2	-2.7	9.7	108	858
	ILF_poultry	-6.1	-29.6	0.1	-26.5	--	--	-48.0	-35.2	-12.9	-6.5	-1.9	0.0	4.6	0.4	12.1	34.0	272
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	-1.7	-13.6	-0.1	-11.9	--	--	-39.6	-15.9	-3.5	-1.8	-0.6	0.0	0.1	-0.2	8.5	86.6	705
VII (3-stage with 2 water stages)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-13.2	-50.4	1.8	-48.5	--	--	-94.0	-72.0	-19.2	-12.1	-4.1	0.2	0.2	-2.0	16.2	182	1,453
	ILF_poultry	-11.7	-23.9	0.0	-21.4	--	--	-48.0	-35.2	-12.9	-6.5	-1.6	0.0	0.5	-0.5	28.6	65.2	521
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	-3.0	-13.9	0.1	-12.2	--	--	-39.6	-15.9	-3.5	-1.8	-0.6	0.1	0.1	-0.2	14.2	148	1,205
VII (3-stage with 1 water stage)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-13.0	-50.0	1.8	-48.1	--	--	-94.0	-72.0	-19.5	-12.4	-4.0	-0.3	-0.2	-2.3	16.1	176	1,403
	ILF_poultry	-12.0	-29.6	0.1	-26.5	--	--	-48.0	-35.2	-12.9	-6.5	-1.9	0.0	3.4	0.1	23.6	66.7	532
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BW	-3.0	-14.5	0.1	-12.7	--	--	-39.6	-15.9	-3.5	-1.8	-0.6	0.0	0.0	-0.2	13.5	145	1,180
VIII[64]	AF	4.2	--	-82.3	-82.3	-52.4	-40.4	--	--	-49.9	-32.4	12.2	-9.3	--	-42.7	-6.3	-6.1	-42.0
	FGF	-4.9	-28.8	-78.0	-29.8	-22.8	-18.3	6.2	6.0	-3.9	-3.5	-12.5	-12.5	-10.8	-13.3	7.4	613	2,247
	ILF_pigs	-4.0	-38.5	-87.3	-41.3	-52.5	-39.2	-94.0	-72.0	-47.1	-30-6	-6.7	6.4	-7.7	-18.7	6.3	20.0	154
	ILF_poultry	3.6	0.5	-85.7	-11.9	-54.6	-42.6	-48.0	-35.2	-45.1	-40.0	10.5	1.3	2.3	-10.6	-15.0	-5.0	-22.7
	MF	-2.5	-32.5	-85.8	-39.7	-51.7	-40.0	-0.5	-1.2	-53.5	-45.7	-2.2	-9.7	-0.6	-22.4	4.1	6.7	28.7
	BW	-2.4	-30.2	-83.1	-37.2	-48.1	-37.1	-38.5	-13.8	-43.5	-31.2	-0.2	-6.8	-8.1	-22.3	3.8	9.5	53.5

Notes: AF – arable farm, FGF – forage growing farm, ILF_pigs and ILF_poultry – intensive livestock farms with the emphasis on pigs and poultry production respectively, MF – mixed farms; BW – Baden-Württemberg.

[63] VII – Scenario VII: Exhaust air treatment, i.e., through the application of biofilter, trickle-bed reactor, 2-stage and 1-stage chemical scrubber, 3-stage filter with 2 water stages, and 3-stage filter with 1 water stage

[64] VIII – Scenario VIII: Combination scenario, i.e., combination of different emissions abatement measures

Appendix III Scenarios' results for NH_3, PM, and GHG emissions in Brandenburg

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	€/ha	kg/ha									kg CO_2e/ha				€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
Reference	AF	686	--	5.9	5.9	10.4	1.9	--	--	10.8	2.2	2,119	819	--	2,938	--	--	--
	FGF	1,089	24.0	1.0	25.0	2.8	0.5	0.3	0.2	3.3	0.9	1,320	562	2,800	4,681	--	--	--
	ILF_pigs	7,021	103	1.0	104	10.2	1.9	4.1	0.7	23.1	4.5	4,448	6,891	1,131	12,470	--	--	--
	ILF_poultry	25,211	811	14.0	825	10.3	1.9	145	24.0	441	129	33,196	69,105	16,779	119,079	--	--	--
	MF	841	10.4	4.3	14.7	7.7	1.4	0.1	0.1	8.3	1.9	2,154	917	1,222	4,294	--	--	--
	BB	923	11.3	4.4	15.7	8.0	1.5	0.5	0.1	9.7	2.2	2,132	1,055	1,051	4,239	--	--	--
		Changes against the reference, in %																
I[65]	AF	-0.9	--	-88.6	-88.6	0.0	0.0	--	--	-0.2	-0.9	-7.8	-3.7	--	-6.6	0.9	--	--
	FGF	-0.3	0.0	-83.7	-3.9	-0.1	-0.1	0.0	0.0	-0.2	-0.6	-2.8	-1.2	0.0	-0.9	3.2	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	MF	-1.8	3.0	-83.3	-26.1	0.2	0.1	4.8	4.9	0.1	-0.4	-5.5	-2.2	2.9	-2.3	3.7	--	--
	BB	-1.3	1.3	-85.1	-27.2	0.1	0.1	0.7	1.7	0.0	-0.5	-5.7	-2.1	1.8	-2.9	2.6	--	--
II[66]	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	-4.9	-10.3	-0.3	-9.9	-3.1	-1.8	8.5	8.3	-1.2	2.7	-12.1	-3.2	-12.9	-11.5	21.3	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	MF	-3.5	-12.5	8.9	-6.3	-2.0	-2.1	4.7	4.5	-1.5	-0.4	3.9	11.2	-11.8	1.0	31.9	--	--
	BB	-2.4	-9.0	4.6	-5.2	-1.1	-1.2	1.3	3.0	-0.7	0.0	1.1	4.9	-11.6	-1.1	27.3	--	--
III[67] (Sows)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	4.2	-7.6	-24.0	-7.8	-0.4	-0.5	--	--	-11.6	-12.0	-7.1	-8.5	-4.8	-13.7	-36.3	--	--
	ILF_poultry	2.5	-3.6	-12.2	-3.7	--	--	--	--	--	--	-4.7	-2.5	-0.5	-5.3	-20.1	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	0.4	-1.1	-0.1	-0.8	--	--	--	--	-0.2	-0.3	-0.2	-0.6	-0.1	-0.5	-26.8	--	--
III (Fattened pigs)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	0.1	--	--	--	--	--	--	--	-1.0	-0.9	--	-1.1	-3.6	-1.1	-195	--	--
	ILF_poultry	1.5	-0.1	0.1	-0.1	--	--	--	--	-0.1	0.0	--	-0.2	-7.1	-1.5	-380	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	0.1	0.0	0.0	0.0	--	--	--	--	0.0	0.0	--	-0.1	-0.3	-0.1	-393	--	--

65 I – Scenario I: Abdication of urea in mineral fertilizers
66 II – Scenario II: Change of housing system
67 III – Scenarios III: Protein adjusted feeding of livestock, i.e., for pigs (sows and fattened pigs) and poultry (laying hens and broilers)

Appendix III Scenarios' results for NH_3, PM, and GHG emissions in Brandenburg (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	**Changes against the reference, in %**														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
III[68] (Laying hens)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	-9.8	-1.1	-1.4	-1.1	--	--	--	--	-43.6	-57.9	-1.1	7.3	--	5.2	271	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.8	-0.2	0.0	-0.1	--	--	--	--	-5.2	-8.8	0.0	0.9	0.0	0.3	273	--	--
III (Broilers)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_poultry	-5.5	-1.7	-1.6	-1.7	--	--	--	--	-2.9	-6.3	-1.3	3.7	0.1	2.2	97.4	--	--
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.4	-0.3	0.0	-0.2	--	--	--	--	-0.3	-1.0	0.0	0.5	0.0	0.1	98.5	--	--
IV[69] (Granulate)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-0.9	-15.6	19.0	-15.3	0.4	0.4	--	--	0.5	1.7	9.6	-0.8	0.0	5.9	3.9	--	--
	ILF_poultry	-1.1	-7.8	8.2	-7.5	0.0	0.0	--	--	0.1	0.3	6.1	0.1	0.0	3.0	4.4	--	--
	MF	-0.2	-6.2	-0.5	-4.5	--	--	--	--	--	--	0.0	0.2	0.0	-0.1	2.7	--	--
	BB	-0.3	-5.6	-0.2	-4.0	0.0	0,0	--	--	0.0	0.0	0.4	0.2	-0.2	0.2	4.9	--	--
IV (Floating film)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-1.0	-15.6	19.0	-15.3	0.0	0,0	--	--	0.5	1.7	9.6	2.5	0.0	4.1	4.5	--	--
	ILF_poultry	-1.1	-7.1	8.2	-6.8	0.0	0,0	--	--	0.1	0.3	6.0	1.6	0.0	2.2	5.1	--	--
	MF	-0.4	-6.2	-0.5	-4.5	0.0	0,0	--	--	0.0	-0.1	0.0	-0.2	0.0	-0.1	5.3	--	--
	BB	-0.5	-5.4	-0.2	-3.9	0.0	0,0	--	--	0.0	0.0	0.4	0.2	0.0	0.2	7.5	--	--
IV (Hexa-cover)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-0.9	-15.6	19.0	-15.3	0.4	0.4	--	--	0.5	1.7	9.6	2.5	0.0	4.1	4.0	--	--
	ILF_poultry	-1.1	-7.8	8.2	-7.5	0.0	0.0	--	--	0.1	0.3	6.0	1.6	0.0	2.2	4.5	--	--
	MF	-0.2	-6.2	-0.5	-4.5	0.0	0.0	--	--	0.0	-0.1	0.0	-0.2	0.0	-0.1	2.0	--	--
	BB	-0.3	-5.6	-0.2	-4.0	0.0	0.0	--	--	0.0	0.0	0.4	0.2	0.0	0.2	4.0	--	--

[68] III – Scenarios III: Protein adjusted feeding of livestock, i.e., for pigs (sows and fattened pigs) and poultry (laying hens and broilers)

[69] IV – Scenario IV: Introduction of the manure storage cover (Scenario IV), i.e., granulate, floating film, Hexa-cover, tent roof, concrete cover, and vehicle-access concrete cover

Appendix III Scenarios' results for NH_3, PM, and GHG emissions in Brandenburg (continuation)

Scenarios	Unit/ Farm type	Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs €/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
		Changes against the reference, in %																
IV[70] (Tent roof)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-1.2	-17.1	20.9	-16.7	0.0	0.0	--	--	0.5	1.9	10.0	2.7	0.0	4.3	4.7	--	--
	ILF_poultry	-1.5	-8.5	9.0	-8.2	0.0	0.0	--	--	0.1	0.4	6.3	1.8	0.0	2.3	5.4	--	--
	MF	-0.5	-7.2	-0.6	-5.3	0.0	0.0	--	--	0.0	-0.1	-0.1	-0.3	0.0	-0.1	5.4	--	--
	BB	-0.6	-6.3	-0.2	-4.5	0.0	0.0	--	--	0.0	0.1	0.4	0.2	0.0	0.2	8.2	--	--
IV (Concrete cover)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-1.5	-17.1	20.9	-16.7	0.4	0.5	--	--	0.5	1.9	10.5	2.7	0.0	4.3	6.0	--	--
	ILF_poultry	-1.7	-8.5	9.0	-8.2	0.0	0.0	--	--	0.1	0.4	6.4	1.8	0.0	2.4	6.1	--	--
	MF	-1.0	-7.3	-0.6	-5.3	0.0	0.0	--	--	0.0	-0.1	0.1	-0.3	0.0	-0.1	11.2	--	--
	BB	-1.3	-6.3	-0.2	-4.5	0.0	0.0	--	--	0.0	0.1	0.4	0.2	0.0	0.2	16.9	--	--
V[71] (Trailing shoe)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-1.3	-7.7	0.0	-7.7	--	--	--	--	0.0	0.0	-0.2	0.0	0.0	-0.1	11.3	--	--
	ILF_poultry	-1.3	-3.4	0.0	-3.4	--	--	--	--	0.0	0.0	-0.1	0.0	0.0	0.0	11.3	--	--
	MF	-1.7	-20.1	-1.6	-14.6	--	--	--	--	0.0	0.0	-1.6	-1.9	-1.9	-0.6	6.7	--	--
	BB	-1.0	-11.1	-0.8	-8.1	--	--	--	--	0.0	0.0	-0.9	-1.2	-1.2	-1.4	7.7	--	--
V (Slurry ex-tirpator)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-1.4	-8.0	0.0	-7.9	--	--	--	--	0.0	0.0	-0.2	0.0	0.0	-0.1	11.7	--	--
	ILF_poultry	-1.4	-3.8	0.0	-3.8	--	--	--	--	0.0	0.0	-0.1	0.0	0.0	0.0	11.2	--	--
	MF	-1.9	-22.9	-1.8	-16.6	--	--	--	--	0.0	0.0	-1.7	-0.7	-1.9	-1.5	6.8	--	--
	BB	-1.2	-12.6	-0.9	-9.2	--	--	--	--	0.0	0.0	-0.9	-0.3	-1.5	-0.9	7.8	--	--
VIa[72]	AF	4.6	--	-0.2	-0.2	-53.1	-41.2	--	--	-51.4	-35.2	-0.4	-15.1*	--	-10.7	--	-5.7	-41.0
	FGF	0.2	0.3	0.4	0.3	-41.0	-31.1	--	--	-34.0	16.3	0.1	-6.6*	-0.1	-1.8	--	-2.3	-16.8
	ILF_pigs	0.4	-1.0	0.0	-1.0	-47.2	-36.2	--	--	-20.9	-15.0	-1.0	-0.1*	0.0	0.8	--	-5.7	-40.7
	ILF_poultry	0.2	-0.7	0.0	-0.6	-46.7	-35.4	--	--	-1.1	-0.5	-0.2	0.3*	0.0	0.4	--	-8.9	-64.5
	MF	2.2	4.4	-1.3	2.7	-52.8	-40.7	--	--	-49.0	-29.6	0.2	-12.4*	3.6	-6.2	--	-4.6	-33.4
	BB	2.3	2.0	-0.7	1.2	-52.3	-40.4	--	--	-43.1	-26.2	-0.1	-10.9*	2.2	-6.1	--	-5.1	-36.4

[70] IV – Scenario IV: Introduction of the manure storage cover (Scenario IV), i.e., granulate, floating film, Hexa-cover, tent roof, concrete cover, and vehicle-access concrete cover
[71] V – Scenario V: Manure land application, i.e., through the implementation of slurry spreading techniques as trailing shoe and slurry extirpator
[72] VIa – Scenario VIa: Reduced tillage, without financial aid

Appendix III Scenarios' results for NH_3, PM, and GHG emissions in Brandenburg (continuation)

Scenarios		Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs		
	Unit/ Farm type	Changes against the reference, in %														€/kg NH_3	€/kg PM_{10}	€/kg $PM_{2.5}$
VII[73] (Biofilter)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-0.9	-16.8	-50.1	-21.6	--	--	-94.0	-72.0	-21.8	-21.5	-16.3	-16.7	-1.5	-24.9	--	14.1	66.5
	ILF_poultry	-12.3	0.0	0.0	0.0	--	--	-36.7	-32.0	-16.0	-9.1	0.0	0.0	0.0	0.0	--	57.0	456
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.5	-1.3	-1.5	-1.4	--	--	-29.4	-12.1	-1.2	-0.8	-0.4	-0.8	0.0	-1.8	--	43.4	291
VII (Trickle bed reactor)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-6.8	-47.8	-12.4	-42.8	--	--	-94.0	-72.0	18.5	-12.9	-6.4	-4.2	0.0	-5.0	9.6	111	824
	ILF_poultry	-10.4	-54.8	-15.4	-47.5	--	--	-36.7	-32.0	-16.6	-10.9	-6.9	-4.3	-0.3	-4.8	5.9	35.9	187
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.8	-9.6	-1.2	-6.9	--	--	-29.4	-12.1	-1.2	-0.8	-0.3	-0.6	0.0	-0.4	6.3	62.2	413
VII (2-stage chemical scrubber)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-6.7	-47.7	-12.4	-42.7	--	--	-94.0	-72.0	-18.5	-12.9	-6.4	-4.2	0.0	-5.0	9.5	109	812
	ILF_poultry	-11.9	-54.7	-15.4	-47.4	--	--	-36.7	-32.0	-16.4	-10.8	-6.8	-4.0	0.0	-4.6	6.7	41.5	217
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.8	-9.5	-1.2	-6.9	--	--	-29.4	-12.1	-1.2	-0.8	-0.3	-0.5	0.0	-0.3	6.7	67.1	447
VII (1-stage chemical scrubber)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-5.4	-48.8	-12.5	-43.6	--	--	-94.0	-72.0	-18.5	-12.9	-6.4	-4.2	0.0	-5.0	7.5	88.0	653
	ILF_poultry	-8.1	-55.2	-15.5	-47.9	--	--	-36.7	-32.0	-16.4	-10.8	-6.9	-4.0	0.0	-4.6	4.6	28.4	148
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.6	-9.7	-1.2	-7.0	--	--	-29.4	-12.1	-1.2	-0.8	-0.3	-0.5	0.0	-0.3	4.9	49.3	328
VII (3-stage with 2 water stages)	AF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-7.5	-48.8	-12.5	-43.6	--	--	-94.0	-72.0	-18.5	-12.9	-6.4	-4.2	0.0	-5.0	10.5	123	915
	ILF_poultry	-9.7	-55.2	-15.5	-47.9	--	--	-36.7	-32.0	-16.4	-10.8	-6.9	-4.0	0.0	-4.6	5.4	33.6	176
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.8	-9.7	-1.2	-7.0	--	--	-29.4	-12.1	-1.2	-0.8	-0.3	-0.5	0.0	-0.3	6.2	63.3	421

[73] VII – Scenario VII: Exhaust air treatment, i.e., through the application of biofilter, trickle-bed reactor, 2-stage and 1-stage chemical scrubber, 3-stage filter with 2 water stages, and 3-stage filter with 1 water stage

Appendix III Scenarios' results for NH_3, PM, and GHG emissions in Brandenburg (continuation)

Scenarios	Unit/ Farm type	Gross margin	NH_3 organic	NH_3 mineral	NH_3	PM_{10} arable	$PM_{2.5}$ arable	PM_{10} animals	$PM_{2.5}$ animals	PM_{10}	$PM_{2.5}$	N_2O	CO_2	CH_4	GHG	Average abatement costs €/kg NH_3	Average abatement costs €/kg PM_{10}	Average abatement costs €/kg $PM_{2.5}$
		Changes against the reference, in %																
VII[74] (3-stage with 2 water stages)	**AF**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	FGF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ILF_pigs	-7.5	-48.8	-12.5	-43.6	--	--	-94.0	-72.0	-18.5	-12.9	-6.4	-4.2	0.0	-5.0	10.5	123	915
	ILF_poultry	-9.7	-55.2	-15.5	-47.9	--	--	-36.7	-32.0	-16.4	-10.8	-6.9	-4.0	0.0	-4.6	5.4	33.6	176
	MF	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	BB	-0.8	-9.7	-1.2	-7.0	--	--	-29.4	-12.1	-1.2	-0.8	-0.3	-0.5	0.0	-0.3	6.2	63.3	421
VIII[75]	**AF**	-0.5	--	-90.5	-90.5	-53.1	-41.2	--	--	-51.9	-37.4	-14.3	-16.3	--	-26.7	0.6	0.6	3.8
	FGF	-5.9	-24.0	-88.6	-26.4	-49.5	-34.6	7.3	7.0	-41.0	-18.8	-22.0	-21.0	-13.5	-16.7	9.7	47.5	372
	ILF_pigs	-3.8	-28.7	96.0	-27.5	-45.7	-34.3	-94.0	-72.0	-50.6	-30.7	14.6	2.5	-7.9	-0.1	9.4	22.9	194
	ILF_poultry	1.5	-48.8	-37.4	-48.6	-46.7	-35.4	-20.6	-15.6	-51.6	-62.8	-31.4	-5.8	-3.4	-36.1	-0.9	-1.6	-4.5
	MF	-4.2	-30.7	-83.3	-45.9	-53.0	-40.5	-1.5	-1.6	-49.7	-31.7	-15.5	-11.1	-1.2	-17.4	5.2	8.5	58.1
	BB	-3.1	-32.1	-86.1	-47.2	52.8	-40.5	-19.5	-8.5	-50.4	-37.6	-15.7	-11.9	-5.5	-20.2	3.8	5.8	34.0

Notes: AF – arable farm, FGF – forage growing farm, ILF_pigs and ILF_poultry – intensive livestock farms with the emphasis on pigs and poultry production respectively, MF – mixed farms; BB – Brandenburg

[74] VII – Scenario VII: Exhaust air treatment, i.e., through the application of biofilter, trickle-bed reactor, 2-stage and 1-stage chemical scrubber, 3-stage filter with 2 water stages, and 3-stage filter with 1 water stage

[75] VIII – Scenario VIII: Combination scenario, i.e., combination of different emissions abatement measures